Stormwater Infiltration Enhancement via Pneumatic Soil Fracturing with Proppant Injection

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1 INTRODUCTION

1.1 DEFINE PROBLEM

Rain gardens are commonly used to increase infiltration in developments since they are capable of treating a flow rate 16 times higher than using a retention pond. For the developer this helps to minimize the area required to treat the increased stormwater flows resulting from the parking lots and other impervious surfaces added to the area. The problem is that although the rain gardens themselves possess a high permeability substrate in the upper layer, the soil surrounding the base of the rain garden is often heavily compacted with low permeability. If a compaction layer at the interface of these soils prevents the base of the rain garden from infiltrating, the rain garden will become overly full frequently. The excess water then could overflow or may simply remain standing for too long after an event, killing the plants and limiting the control measure's effectiveness, turning what was meant to be a stormwater control measure into a swampy mess.

Figure 1: Failed Rain Garden.

Figure 2: Healthy Rain Garden.

1.1.1 SUCCESS CRITERIA

Success is defined as developing an inexpensive and versatile device that can significantly enhance infiltration within a stormwater control measure's heavily compacted soil. This device will work by making the soil surrounding the sides and bottom of the rain garden more permeable by increasing the percentage of macropores present in the treated soil's pore size distribution. This can be achieved by creating a bore hole and a series of interconnected fractures which connect to the surface.

The primary success criterion is concerned with increasing infiltration sixteen-fold after application of the treatment. The treatment must be relatively quick, affecting 500 square feet in under three hours with one or two workers. The treatment must be inexpensive, costing less than $5000 to manufacture and must be cost-effective with regards to its operation and maintenance on a square foot basis. The treatment must not negatively impact the environment. It is desirable to keep any vegetation in the rain garden intact so that the root systems can continue filtering infiltrated stormwater. The treatment must be versatile and capable of maneuvering steep slopes and variable terrain.

1.1.2 PRIORITIZED SUCCESS CRITERIA

1. Must function in heavily compacted clay type C, D soils.
2. At least a sixteen-fold increase in infiltrated depth over a 12-hour time period.
3. Has an expected Maintenance/Operating cost of less than \$1 per ft^2 of treated area
4. Can treat an area of 500 ft^2 in no more than 3 hours with two relatively unskilled workers
5. Variability of acceptable working terrain
6. Minimize environmental impact
7. Can be used before installation of control measure and on existing control measures
8. Maximize time between treatments of the same area on a basis of years

2 UNDERSTANDING

2.1 INFILTRATION

The inherent factors affecting soil infiltration are soil texture (percentage of sand, silt, and clay), the presence of cracks and macropores, and hydraulic conductivity. The history of the soil's exposure to surface stress affects the presence of macropores at a deep level. Soils that have not been compacted have a soil structure that provides a better pore size distribution. The physical arrangement of pore size distribution in relation to the surface flow is the driving factor for infiltration rate. The distribution of the pore sizes and the way they are connected to the surface is what determines the permeability of the site, which is a measure of the rate of infiltration in meters squared per millidarcy.

The following represents information from the Knoxville Stormwater Manual on Rain Gardens: [14]

The recommended minimum infiltration rate is at least 0.5 inches per hour, but ultimately it depends on the type of infiltration system being implemented and the desired water quality treatment involved. The primary concern for rain gardens is for drawdown to occur within 72 hours using a safety factor of 2.0 to account for wet weather water table conditions.

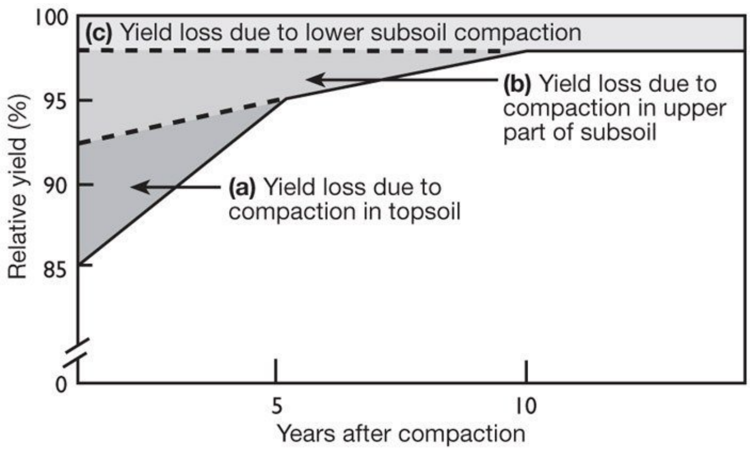

Figure 3: Yield Loss from Compaction. An internal study by PSU's extention office found that deep compaction will not reduce over time and must be broken up with equipment.[11] Deep compaction leads to smaller plants due to a reduced maximum root depth, which in the context of a rain garden means less transpiration and less infiltration.

All infiltration systems should be inspected several times the first year and at least twice a year thereafter to determine if they are still functioning properly.

An infiltration basin or trench must have at least 3 feet of separation from seasonal high groundwater and at least 4 feet of separation from bedrock. Coarse soils are not as effective in filtering groundwater; therefore, at least 6 to 8 feet of separation from seasonal high groundwater for sand and gravel soils should be provided.

In general, infiltration basins are not effective in the Knoxville area due to clay soils and shallow bedrock conditions.

The infiltration basin volume should be sized to handle at least 85 % of the average annual runoff, using the formula for volume capture (as discussed previously). The maximum allowable depth should be calculated using a safety factor of 2.0 to represent the uncertainty of infiltration due to construction methods and potential clogging:

$$Maximum\ ponding\ depth = (24 hours) * \frac{infiltration\ rate}{factor\ of\ safety}$$

$$Minimum\ surface\ area = \frac{required\ volume}{maximum\ ponding\ depth}$$

It is greatly desired that runoff be treated using one or more stormwater treatment BMPs prior to discharging toward a sinkhole or other natural depression.

The four major concerns with infiltration systems are clogging, potential impact on other structures and properties, accumulation of heavy metals, and the potential for groundwater contamination.

2.1.1 RAIN GARDEN FAILURE

Seattle has implemented rain gardens in the waterfront district to reduce flooding. The gardens, which resemble shallow, sparsely-planted ditches running between the road and sidewalk, fill with water and remain filled. A serious problem went undiscovered: the presence of underground spring water and shallow groundwater. Some of the more than 90 rain gardens are actually tapping this water, and adding it to the rain runoff to create continually soggy ponds. Additionally, there was more fine-grained soil that does a poor job soaking up water. Green infrastructure experts say that even though the soil in Ballard is often composed of clay and dense earth called “glacial till” that’s tricky to work with, there are solutions. [23]

Figure 4: Failed Rain Garden. Fines and organic matter can clog the basin of rain gardens, preventing them from draining.

The Community and Environmental Defenses Services (CEDS) assists groups in auditing Rain Gardens throughout a watershed and across the nation. Typically, volunteers meet on a Saturday morning for a one-hour training session. They form into teams to evaluate several facilities and return to the meeting place by noon to report their findings. The survey results identify shortcomings in the existing programs to keep these facilities working at their best. As an example of one such audit, on May 8th 2012, 26 volunteers participated in a Rain Garden-Bioretention Evaluation training session at the West County Library. Overall, the volunteers found a third of the facilities were in good condition. However, 43 percent were in poor condition providing essentially no water quality protection. [5]

CEDS states that in prior surveys of all stormwater facilities, they have found a third to 100 percent to have failed depending upon type.

There are a variety of reasons for rain garden failure, such as water table height in Seattle, however, the problem addressed by this design is preventing rain garden ponding due to inadequate draining from compacted soils with low permeability at the base of the rain garden.

2.1.2 FRACTURING AS A TREATMENT

One method of breaking through the compacted layer that forms in the bottom of failed rain gardens is by piercing that layer with a tube and injecting a pressurized fluid into the soil. The fluid then fractures the soil as it escapes toward the surface. The amount of pressure required and type of fractures formed are dependant on the soil type and the depth of the injection.

"Environmental fracturing technologies are techniques that enhance or create openings in bedrock or soil with low effective porosity, such as clay, to help soil and groundwater cleanup methods work better. The enhancements are referred to as secondary porosity fractures and joints. Environmental fracturing can be used to make primary treatment technologies such as pump and treat, in situ chemical oxidation/reduction, in situ bioremediation, or soil vapor extraction more efficient." [8]

2.2 HISTORICAL DESIGN APPROACHES

Several industries have done prior work researching and developing systems designed to fracture the soil for different purposes including: septic soil treatment, plant amendment, and hydrocarbon extraction. Before designing this system these three industrial applications were considered and aspects of each system are present in our proposed design.

2.2.1 SEPTIC SYSTEM TREATMENT

Septic field treatment systems are used to break up the soft soils of a septic field in order to increase the flow rate of the effluent through the ground are a good example of small scale soil fracturing. The Terralift is one example of this type of system which uses pneumatic pressure at a depth of about 8 feet. The air carries with it polystyrene beads, which fill the fractures created by the pressurized blast. Although polystyrene has a relatively low compressive strength, failing at 14 psi, it can work for soft soils that don't experience any surface loading.[4] The tanks, hoses, and air compression system of the Terralift were analyzed visually and partially replicated in our design.

2.2.2 IN-SITU PLANT AMENDMENT

Hand held plant amendment systems can be used to deposit fertilizer deep into the root zone of plants to remedy nutrient deficiencies without removing the plant. The Grow Gun Amendment System use an auger to drill a pilot hole into the soil 4 to 6 feet deep before injecting a rod. The rod is pressurized with air in order to cause soil fracturing, then using a separate pump a fluid containing granular fertilizer suspended in liquid is pumped into the soil fractures to provide a change in soil chemistry without requiring the removal of the plants already living there.

2.2.3 HYDRAULIC FRACTURING IN THE PETROLEUM INDUSTRY

The petroleum extraction industry uses high pressure hydraulic fracturing at the bottom of bore hole that extends thousands of feet beneath the surface resulting in primarily horizontal fracturing due to the vertical confining stress seen at such extreme depths. The fractures extend hundreds of feet through rock beds. Initially, a highly viscous fluid carries suspended granular particles into the fractures to fill them and prevent recompression of the void. The particles will settle along the path and are usually fed in a gradient with the smallest first, so that the microfissures formed at the ends of the fractures are filled with the smallest grade and are not first clogged by larger particles.

2.3 PROPPANT

Proppant is the material used in fracturing systems which props open the fracture to prevent the closure for an extended period of time. The petroleum extraction industry uses it to increase the flow rate during the extraction process. Terralift uses it to hold the soil open and increase the rate of flow of septic effluent through the ground. To accomplish these goals, several materials are available: Frac sand, polystyrene, other designer proppants with biochar.

Proppant	Compressive Strength (PSI)	Density (g/cc)	Cost($)	$\theta\ \frac{m^3}{m^3}$
Biochar	5,000	0.6 to 1.5	0.50	0.50
Sand	2,000	2.65	0.05	0.30
Styrafoam	60	0.10	1.85	0.95
Ceramic	10,000	2.5 to 3.5	high	—
PHB	5,800	1.18	high	—

Table 1: List of Proppants and their Properties. Biochar's density varies greatly depending on moisture conditions. Styrofoam has a high pore volume, but the average pore size is on the order of 315 nm. The ceramic and PHB based can be designed to any size diameter required, which gives varying porosity, but their cost is too high to be considered for rain gardens. The costs considered in this chart are based on a 1/2 gallon volume injection.

Proppant performance is driven by three factors: void space, settling rate, and compressible strength. The proppant must allow for high flow, stay in solution long enough to deposit itself in the fractures, and it must have enough strength to retain it's structure over the long term. Coarse biochar has better performance than coarse sand of the same 2 mm diameter for all three categories. Stokes equation shows that the settling rate is determined by the difference in density relative to the fluid and the viscosity of the fluid. Details about this are available in the proppant fluid requirements calculations section of the appendix. According to stokes equation, since biochar is about 1.48 grams per milliliter when fully saturated compared to the 2.6 grams per milliliter density of sand, it will settle slower. Before saturation, biochar has a much lower density of about 0.6 grams per milliliter which means it will float. Additionally as a result of the creosote oils produced during the pyrolosis process during manufacturing, biochar has a hydrophobic surface and is slow to absorb water. The particles used in this design are between 1 to 2 mm which is coarse and will have a lower surface area to weight ratio than finer grades which are more difficult to mix. This should allow the biochar to mix reasonably well with fluid according to prior research. [31] Preliminary testing on the mixing properties of 1 to 2 mm biochar was performed on a mix table for 30 minutes and allowed to sit overnight. The biochar was prepared by breaking down full sized natural char coal chunks, then sieveing through a #18 and # 10 mesh. The test resulted in the entire addition floated even after 30 minutes on a mixing table. However, when left over night it separated and about 50 % of the particulates sank, while the remaining 50 % stayed on top of the water. During the prototype injection testing, the biochar was added only a few hours before test and was still floating in the 50 % mixture during the injection. This seemed not to matter, as biochar was seen exiting the fractures in the surface of the soil, however further testing will be required to know the effects it may have on fracture shape and infiltration rates.

In addition to it's low density, the shape of biochar allows it to form both a greater pore space and diameter. The larger the diameter of pore space within the fractures, the more quickly infiltration will occur. [26] Coarse biochar contains about about 0.5 porosity of media injected, about 42% greater than the 0.35 porosity of sand. An additional advantage here is that less weight of media will need to be carried to the injection since the pore space within the fractures will be greater and the overall density is less.

Biochar can be manufactured at any size that might be required and its surface can be treated to have various adsorbtion properties. Maximum proppant size is primary limited by the impellers ability to pump the liquid mixture and the nozzle diameter at the end of the injection rod. The hole left after the injection, however, can tolerate much larger diameter sizes. Since larger diameters lead to larger flow, a 0.5 inch diameter proppant will be used to fill the 4 foot deep, 1.5 inch diameter cavity left in the soil.

2.4 ENVIRONMENTAL APPLICATION

2.4.1 STORMWATER CONTROL

MS4 phase II stormwater regulations are defined by the EPA and apply to operators of regulated small municipal separate storm sewer systems, with a population size between 100,000 and 250,000. Municipal separate storm systems have drainage systems which carry runoff from storms separate from sewage discharge. The regulated subset includes approximately 7,000 systems owned by the local, federal, and state governments. The NPDES oversees permitting and has the ability to wave requirements for some of that subset and decide which systems are regulated on a basis of how near the discharge is to sensitive water, the population density, significant contributors of water pollutants, and systems with ineffective protection of water quality by other regulation programs.

MS4 phase II regulations provide an incentive for the operators of storm water systems to implement the best management practices for reducing the volume of runoff and the concentrations of pollutants that runoff contains. The infiltration enhancement device detailed in this paper is designed to accomplish both of those goals in situations where the subsurface soil has become too compacted to handle the stormwater flow adequately. As the population of other communities grow, more systems are expected to fall under MS4 phase II regulations over time.

2.4.2 POLLUTION ADSORBTION

Heavy metals and petrol waste are present in runoff from road ways which rain gardens are often placed near. Since rain gardens experience a highly concentrated flow, a high adsorption rate is needed to properly filter that flow through the soil substrate. The addition of biochar to the highest infiltration areas of the soil mean that it will be exposed to an even higher concentration of pollutants than the rest of the garden. This arrangement is ideal since biochar's negatively charged surface provides an electrostatic attraction to the positively charged heavy metals and the porous structure provides a method of physical adsorption. The hydroxyl groups on the surface of biochar also provide a site for precipitation and complexation to occur.

When runoff contaminated with metals streams into a rain garden, multiple studies show that the pollutants are largely adsorbed by particles in the soil and mulch. A small fraction of the metals are taken up by plants. But even if all the metals are being held in the rain garden, it's still not considered a dangerous concentration of toxins for soil. A 2013 study concluded that it would take about 20 years for rain garden soils soaking up runoff to reach EPA limits for the amount of heavy metals allowed in recycled sewage waste used as compost. [22]When Northwest counties tested for metals in the sediment that was scooped from the bottom of stormwater ponds or rain gardens that drain parking lots and other city surfaces — material that would likely have higher levels of metals than your average residential rain garden — they found that the contamination levels were still below soil and compost standards meant to protect human health.

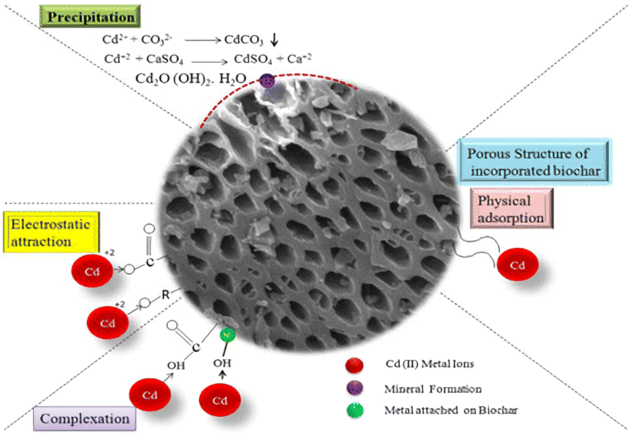

Figure 5: Biochar Methods of Pollutant Removal. Electrostatic attraction, complexion, physical adsorbtion, and precipitation can remove to positively charged heavy metals from water flowing through the proppant filled fractures created by the injection device. [30]

The rate of removal of pollutants by biochar is primarily dependant on the surface area and the functional surface that biochar has. Since biochar is made from wood through a pyrolysis process. The temperature at which this process occurs is related to the functional groups left on the surface and the degree to which the pores of the biochar are already occupied. Higher temperatures lead to greater surface area and better adsorbtion ability. Activated carbon is essentially biochar that has been heated for an even longer time at a higher temperature.

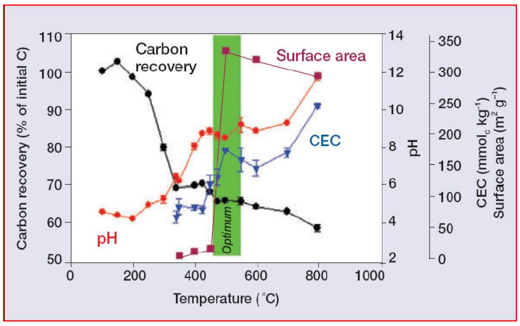

Figure 6: Biochar Surface Area. The surface area and carbon oxygen ratios are both a function of pyrolysis temperature. [13]

2.4.3 BIOLOGICAL EFFECTS ON INFILTRATION

Biological life is correlated with the pore size distribution and can contribute to the long term stability of soils with a high percentage of macropores. [18] After fractures have been created in the compaction layer such that there are openings with a density less than 1.6 $\frac{g}{cm^3}$ roots and fungi will penetrate the layer and give the soil more structure. The population of fungi present has been correlated to the amount of organic matter present in the soil, further justifying the use of biochar as a proppant. By dispersing biochar through out the soil fractures you provide a place for fungi to live, those fungi can create up to 2.5 atm of penetrating pressure at the tip using of their hyphae using turgor pressure on their cell walls over a very small area. Fungi increase soil stability by penetrating even further into the microfractures than plant roots could, and may contribute to the longevity of the infiltration increases induced by this treatment. These fungi can also connect with plant roots to exchange nutrients and water which could benefit the plant by giving it a deeper network to pull water from during droughts. The soil might then drying more thoroughly, while still allowing the plants to survive which could contribute to an increase in infiltration during the next storm event by increasing the initial storage available.

3 POSSIBLE DESIGNS

3.1 SUBSOILER DESIGN

A subsoiler is a well known agricultural implement used to remedy subsoil compaction. By combining this existing method with a proppant injection system, the fractures could be held open to a higher degree, over a much longer period. This design works by using a tractor's 3 point hitch to mount a wing-tined subsoiler which has been modified with an injection tube mounted on the back of the tine, with the outlet at the base. The subsoiler will lift the soil and a fluid proppant mixture will be injected into the void created by the winged tine. Above the tine a cylindrical hopper with an agitator and centrifugal pump with a solids capable impeller is plumbed to the injector pipe connected to the rear surface of the subsoiler arm. As the subsoiler fractures the soil, To maximize infiltration the rip must be held open, therefore the pressure of the pump and speed of the tractor would be set to allow the slurry to fill the upper portion of the trench as well so that the increased void space would be conuious to the surface. Biochar would serve as a proppant in this system to keep the fractures open. The proppant may require a high viscosity solution or a coating, such hydrogel to keep the solids mixed and prevent mature settling. The particle size of the proppant should be relatively uniform, so that proppant flows well from the pump to the fractures in the soil.

A subsoiler design would have the advantage of using a known working method and the approach is mechanically simple, fast, and cheap. The limitation of subsoiling is that the soil must be dry and it is only recommended that a ripper be used during mid-summer when soil moisture is at its lowest. The reasoning for this is related to the plasticity of clay soils under moist conditions, the relationship of which is defined by the atterburg limits which are detailed in the moist soil conditions section of the appendix. Additionally, the use of a tractor could further compact the soil you are trying to treat. For these reasons, this approach was discarded.

3.2 SOIL AMENDMENT

In addition to physically loosening the soil, amendments incorporated in combination with digging and tilling can significantly benefit soil infiltration. For example, a thorough mixture (by volume) of 50 percent sand, 30 percent organic compost and 20 percent excavated soil incorporated 6 inches deep in the rain garden bottom can enhance infiltration. Caution should be used when combining sand and clay soils; unless the sand percentage is relatively high, the mixture will function more like concrete than soil. A final strategy is simply making the rain garden bigger to accommodate the slower infiltration time of clays by combining aeration and soil amendment.

Structure type		Permeability[1]
Platy	- Greatly overlapping	From very slow to very rapid
	- Slightly overlapping	
Blocky		
Prismatic		
Granular		

Figure 7: Soil Structure. Using aerifiers that remove soil cores and filling the holes with chopped organic material will improve the soil gradually by changing the structure and soil type.

3.3 PNEUMATIC FRACTURING

The use of pneumatic fracturing to treat soil has been done before, as detailed in section 2.2.1, however, it has not been done on a large scale as a means of increasing infiltration of compacted soils. Using pneumatic fracturing to treat heavily compacted soils will provide new pathways for the water to flow through the soil by inducing fractures. The larger the fracture size created, the more flow of water these pathways will be able to withstand. The pneumatic fracturing will also increase the pore size distribution of the soil by lifting and breaking the soil in the fracture cone.

The primary benefit of pneumatic fracturing when compared to the other methods above is the ability to be used as retroactive treatment. Both design approaches previously mentioned require heavy equipment, while a pneumatic fracturing system will be able to function without the use of heavy equipment. As seen in figure 8, the soil that would need to be treated is underneath the rain garden, as it is the soil hindering the flow of water. Heavy equipment would destroy a rain garden that has failed due to heavily compacted subsoil. Due to this issue, the only way to treat failing rain gardens with the previous approaches would be to remove the rain garden, treat the subsoil, then replace it. As seen in figure 9, the pneumatic soil fracturing device can penetrate the rain garden to fracture the subsoil with minimal damage to the rain garden.

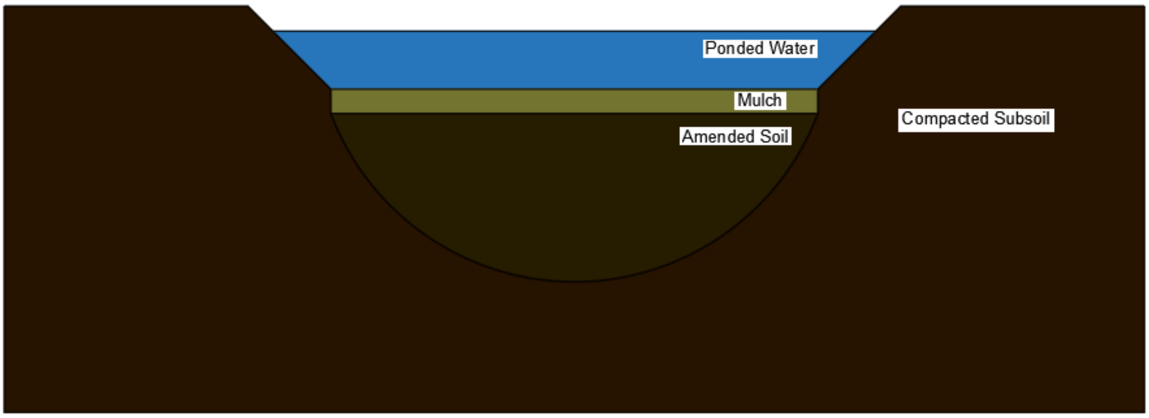

Figure 8: Cross section of a rain garden with compacted subsoil underneath.

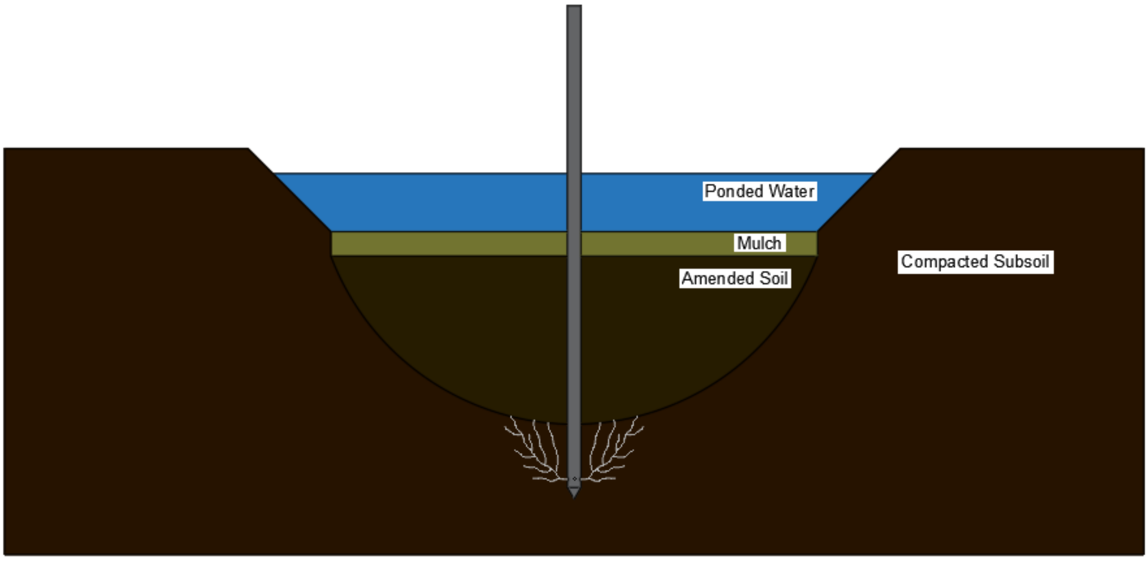

Figure 9: Cross section of a rain garden and subsoil that has been treated with a pneumatic fracturing device through an injection tube.

4 DESIGN

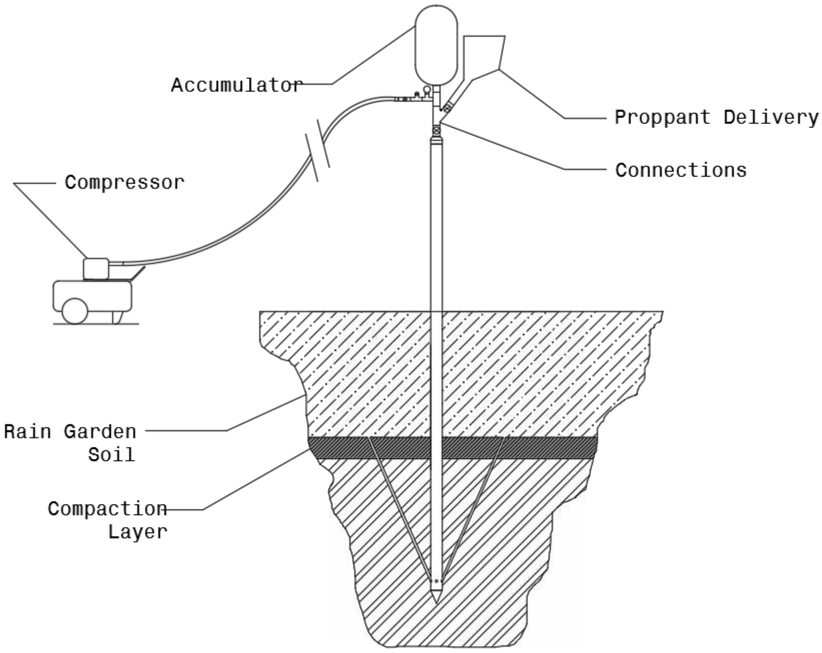

Figure 10: Full System Diagram.

The design sequence involved properly selecting components sufficient to handle the conditions required to inject a rod, fill it with a proppant fluid mixture, then by pressurizing the tube that proppant fluid mixture will be force into the soil, fracturing a cone shape from the rod to the surface which becomes full of proppant, at which point the rod is removed from the ground.

The air that is to be utilized for the pneumatic fracturing of soil must first be pressurized, and that pressurization is accomplished with a compressor. For portable applications, such as the soil fracturing system being designed, reciprocating compressors are generally used. The target air flow rate and pressure of 15 cfm at 100 psi was determined by analyzing the peak stress of compacted clay soil. Any pressure above the peak stress will induce fractures, and in order to produce larger macropores and cracks, the pressure must be excessive. The pressure in excess of what is required is known as overburden pressure and the magnitude of the overburden pressure relates to the fracture pattern formed in the soil. The flow rate required to fracture the soil in question need only exceed the natural permeability of the soil. Given that the permeability for compacted clay is approximately 3.28*10-9 ft/s, it was determined that virtually any flow rate emanating from our device's nozzle would suffice in breaking up the soil. Therefore, the chief concern is providing the appropriate volume of air consistently to the soil at the required pressure. Typical flow velocities in a compressed air system are 15 to 20 ft/s, and should never exceed 30 ft/s. Given the desired pressure, pipe diameter, and velocity, the flow rate in cfm was approximated for use in pressure drop calculations. The principle equations for determining the peak in situ stress of compacted clay was derived from The Fundamentals of Fractured Reservoir Engineering by T.D. Van Golf-Racht in equation 1.

$$
\begin{aligned}
\sigma' &= \sqrt{\sigma_1^2 + \sigma_2^2} \\
\sigma_2 &= 0.5\,\sigma_1 \\
\sigma'_{max} &= \sqrt{\sigma_1^2 + 0.5\sigma_1^2} \\
\sigma'_{max} &= \sqrt{50^2 psi + 0.5 * 50^2 psi} \\
\sigma_1 &= 62\,psi \\
b
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
\phi'_{compacted\ clay} &= 22^{\circ} \\
\tau_{max} &= \sigma'_{max} * 2tan(\phi') \\
\tau_{max} &= 62psi * 2tan(22^{\circ}) \\
\tau_{max} &= 49\,psi
\end{aligned}
\tag{2}
$$

Based on the literature, the typical angle of friction for compacted clay soils is 22 degrees, and typical normal stress in the soil is 50 psi as shown in equation 1. The shear strength of 49 psi must be overcome in order to induce fractures in the soil as shown in equation 2.

4.1 COMPONENTS

4.1.1 CONTROL SYSTEM

The hand operated system will require two operators to move rapidly, but since a second person would already be needed to help move the equipment around the site this was considered acceptable. Hand operated system was favored for reliability and the ability to adjust the rate of application in the field to manage the high variability of soil type as well as the varying depths of rain gardens.

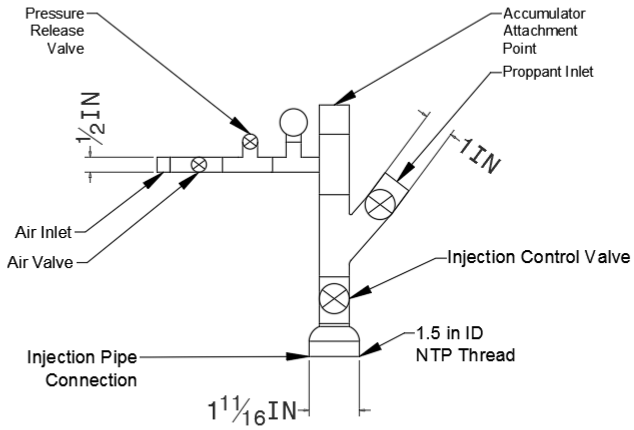

Figure 11: Connections. Before injection, a funnel is connected to the proppant inlet with and the pressure release valve open, 0.5 gallons of proppant mixture is loaded into the 0.55 gallon injection tube. After shutting the proppant valve, the air inlet is turned on. At this point, if an accumulator is attached it will normalize to the pressure flowing into it. After the pressure gauge stabilizes on 130 psi, the air inlet is closed, Finally the injection control valve is opened and proppant mixture fractures the ground around the injection site.

4.1.2 PROPPANT DISTRIBUTION

The proppant will be stored in 1 gallon jugs for easy dosing of the half proppant, half water mixture. These jugs should be premade the night before application to ensure that the biochar has had time to absorb some of the water, otherwise it may be too hydrophobic to flow into the fractures properly. After the injection rod has been driven into the ground, the 0.5 gallons of proppant will be poured in through the proppant inlet as shown in figure 11. The flow of proppant in is controlled by the valve at the proppant inlet funnel seen in figure 10 which will need to be closed during the injection. After the injection has taken place and the tube has been removed, the 0.5 gallon void left will be filled with the same proppant mixture. Rather than try to source multiple sizes of proppant and use a larger size for backfill, a single size was chosen since it will not limit the drainage and will have a higher surface area which will increase the ability of the same volume of biochar to adsorb pollutants.

Coarse biochar with a diameter of about 2 mm offers a 0.53 volume pore space per volume media ratio which is at least 42% greater than comparable sand at the same diameter due to the rod like shape, in tests this has led to a 15% higher hydraulic conductivity. The additional pore space leads to an increased permeability due to the large diameter of the fractures created and the high amount of pore space available for flow within the fractures.

The treatment should last for a long time. The exact half life depends on the temperature of the pyrolosis and the resulting O:C ratio. For a high temperature biochar with an O:C ratio of 0.2, the half life is 1000 years. This means that in 20 years, only 4 % of the biochar would have broken down. See the proppant breakdown subsection of the appendix for the detailed calculations. For lower temperatures this number can be as high as 8 %. Since the rate of losses is highest at the initial injection time, there seems to be no need for concerns about performance degradation over time due to carbon loss.

Although the biochar is unlikely to degrade, it may eventually become integrated into the soil, so that the flow paths become closed. To calculate an accurate expected life for these treatments will ultimately require empirical data.

Another concern was that the biochar could shrink and swell as moisture conditions change, but research on the hydraulic conductivity found that there was no swelling after the initial hydration after the pyrolysis manufacturing process. [27]

Overall this proppant injection system should provide an adequate rate of operation to meet the needs of the client and is expected to last long enough to justify the treatment time and expense required by this system.

4.1.3 INJECTION TUBE

An injection tube 6 feet long was designed to be driven to a 4 foot depth with two feet remaining above the surface for easier extraction. The 2 feet above the surface allow for methods such as the pneumatic jack removal to occur. The pneumatic jack needs to be placed under the collar that will be attached to the tube, requiring an excess length above the surface. When the tube is being inserted, the ease of insertion will determine how long it takes to treat a required area. To resolve this concern, the tube end has a cone shaped nozzle fitted to it in order to reduce the driving force required by the device driving the tube into the ground.

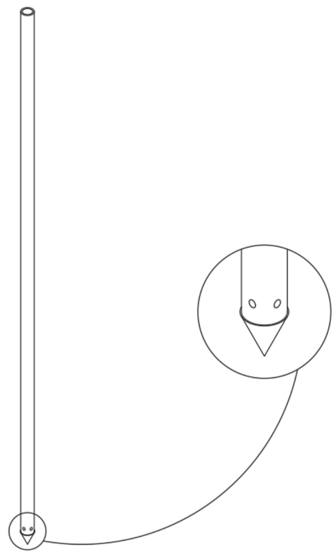

Figure 12: Injection Tube. This 6 foot long tube has 4 holes of a $\frac{5}{16}$ inch diameter drilled 90 degrees apart 1 inch above the start of the cone shaped tip.

The injection tube had to be designed around the structural analysis of the material under the expected loading scenarios. The loading scenarios can be separated into three major concerns: impact loading, pressure vessel analysis, and buckling force. As seen in Appendix A.2, an injection tube prepared from A500 steel will be able to withstand the expected loading. The final safety factor for the design of the injection tube is 2.16, relating to the impact loading.

The injection tube design also had to consider the possibility that fluid will escape between the outer wall of the tube and the surface of the soil. If enough fluid escaped in this direction, the pressure on the soil would drop before significant fracturing could occur. Leakage was quantified by modeling flow through an annular section around the tube. The model constructed confirms that the amount of flow possible in the annulus will not effect the fracturing as long as the gap of the annulus what would be expected when injecting a tube straight into the ground is minimal. The calculations for this are included in appendix A.2.

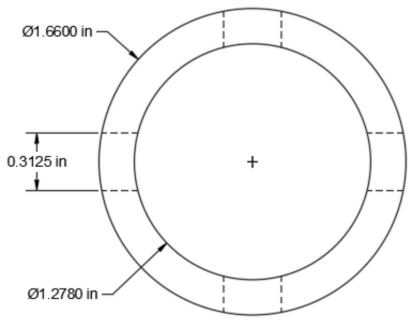

Figure 13: Cross Section at Injection Holes.

4.1.4 TUBE INSERTION AND REMOVAL

The tube will be inserted using the 99E-X Basic Man Saver Post Driver 2" Outer Diameter. The Post Driver is a pneumatic hammer that drives down on a collar attached to the outside of the tube.

Figure 14: Basic Man Saver T-Post Driver.

As shown in Figure 8, the Man Saver drives the post into the ground by hammering against the collar clamped onto the side of the post. To account for the length of the post driver, the collar will be attached 26 inches from the top of the metal tube.

The following lists the manufacturer's specifications for the Mansaver: [15]

Pressure = 70 psi

Flowrate = 2.5 cfm

Kinetic energy = 2872 lb-ft

Length = 25 in

Weight = 32 lbs

Strokes per minute = 80-85

The tube will be removed from the soil using the Xtremepower US 8 Ton Air/Hydraulic Long Ram Jack. [28]

Figure 15: Xtremepower Long Ram Jack. The long ram jack will use 8 cfm of air at 120 psi supplied by the air compressor. The jack is capable of lifting 16,000 lbs which is well above the required force calculated in the tube removal section of the appendix.

The follow lists the manufacturer's specifications for the Long Ram Jack: [28]

Minimum height = 23-3/4 inches

Maximum height = 42 inches

Capacity = 16,000 lbs

Pressure = 100-120 psi

Flowrate = 8 cfm

Ram Dimensions = 1-1/3-in Diameter x 17-1/2-in Length

Air Valve and Inlet = ¼-in x 18 NPT Quick Disconnect

The long ram jack will push up against a 2x2x4-in A36 steel bar welded onto the Man Saver Post Driver collar. After the tube is in the ground, this collar will be unscrewed and reattached 24 inches above the ground, near the top of the tube. The long ram jack will then push the tube 18 inches out of the ground. After the tube is raised 18 inches, the tube will be manually removed from the soil. After the tube is removed, a cylindrical void with about 0.5 gallons of volume will remain in the soil. The void will be back filled with proppant fluid mixture.

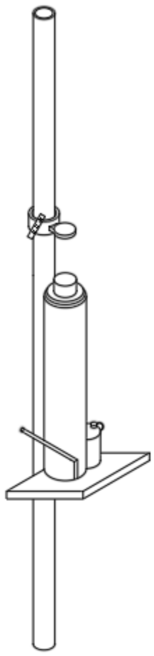

Figure 16: The long ram jack will be placed on a square piece of wood to keep the jack from digging into the ground. It will push up against the collar attachment.

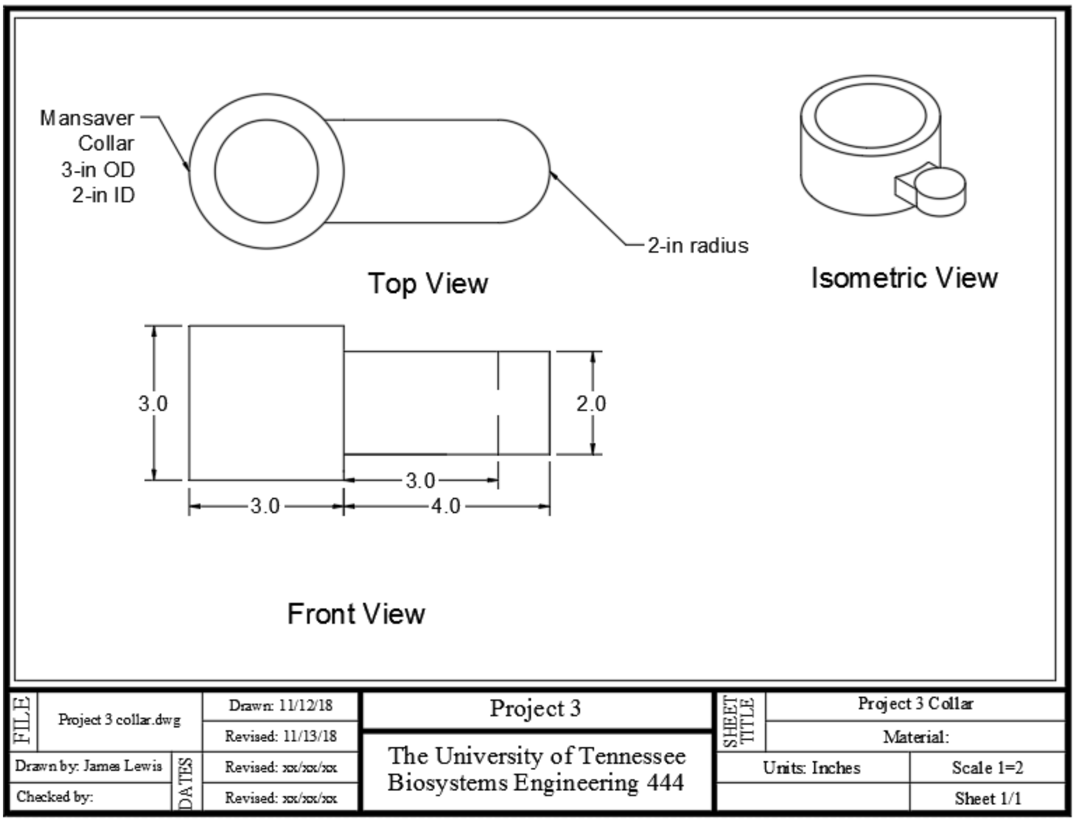

Figure 17: The above AutoCAD drawing lists the dimensions of the collar attachment. It will be machined from a 2x2x4 A36 steel bar.

4.1.5 COMPRESSOR

After reviewing other systems used in industry and their operating pressures, a maximum required pressure of 120 psi for this pneumatic system was assumed to be satisfied by a single stage gas powered portable compressor. Appropriate flow rates ranging from 10 cfm to 15 cfm will induce fractures in the soil and fill the conically oriented fracture volume that is expected after treatment. The compressor will be used to build pressure in the accumulator before the injection and the flow rate will determine the fill time of the accumulator, which according to the calculations will only take a few seconds. The calculations for this can be found in the accumulator calculations subsection of the appendix. Since the gas powered compressor will be heavy and loud, it can be left on the trailer and connected using an air hose. The air hose chosen will be heavy duty $\frac{1}{2}$-inch rubber or polyurethane and will be covered with an extra rubber or nylon layer to prevent kinking to ensure that the reliable air pressure is delivered. Calculations for pressure losses and a pneumatic circuit diagram are found in Appendix A.3.

4.1.6 ACCUMULATOR

For the prototype design, an accumulator which was sized to be 66 % of the volume of the injection rod was added the top of the system to increase the initial air available to the system. The prototype control system allows for removal of the accumulator. Since the injection velocity seemed to occur rather slowly, it may not be required, and further testing of the fracture pattern is needed to determine whether this component is beneficial to the system. One other benefit of an accumulator is that by having only a set volume of pressurized air to inject limits the possibility of tube ejection, which would be a hazardous scenario. Given the limited flow rate out of the $\frac{5}{16}$-inch holes which are oriented 90 degrees off vertical, this situation doesn't seem likely as long as reasonably high frictional coefficients exist between the tube exterior and soil surface. Since these conditions may exist in ponded rain gardens it is important to consider ways to reduce the probability of ejection.

4.1.7 SAFETY CONSIDERATIONS

Figure 18: Whipcheck. A Safety tether connects to each side of a pressure connection protect the operator against whipping in the case of connection failure.

Ejection a major safety concern for this injection system. Pressure could build up in the bottom of the bore hole below the pipe, overcoming the frictional resistance on the sidewalls and sending it up and out of the soil. To some degree this will be limited in a configuration that uses an accumulator since there will be a maximum volume of air injected so if the system were to eject and it would run out of energy quickly.

One approach that has been considered is to use a solenoid valve in place of a ball valve to control the injection. The solenoid valve could be attached to an accelerometer sensor, ultra sonic sensor detecting ground depth, or simple mechanically tethered switch to detect lift and close the valve.

Other safety concerns in this system are related to the pressurized components. One of the most dangerous failure modes would be if the tube were to launch itself out of the bore hole. This possibility is mitigated by the low volume of air in the accumulator and the relatively low pressure of the system itself at 130 psi. Another possibility is fore the pressurized air hose running between the tube and the compressor failing at a point before it reaches the tube. This would create a whip propelled by the flow of air exiting the tube which can be mitigated by having a relatively low flow rate to fill the accumulator and using whip checks at the connections since that is the most likely point of failure. The only maintenance required in this system is a regular draining of the pressure vessel attached to the compressor since water tends to accumulate in compressed air tanks, causing failure by rusting and weakening the bottom inside the vessel.

5 PROCESS ANALYSIS

5.1 MODEL

"Pneumatic fracturing is the injection of gas at high pressure and flow in order to create fractures or fissures in soil or rock matrix. Fractures or fissures occur when the pressure of injected gas exceeds the natural in situ stresses and the flow rate exceeds the natural permeability of the soils. In soil formations, pneumatic fracturing enhances the permeability by creating fracture networks; while in rock, the effect is dilation and extension of existing discontinuities; thereby improving the interconnection between existing fractures. The immediate benefit of pneumatic fracturing [for bioremediation purposes] is improved access to subsurface contaminants so that liquids and vapors can be transported and extracted rapidly, which represents a cost savings in the installation and operational phases of a remediation project. Another advantage of pneumatic fracturing is that it can be applied within existing remedial systems as an enhancement and beneath or adjacent to existing structures and/or utilities."[26]

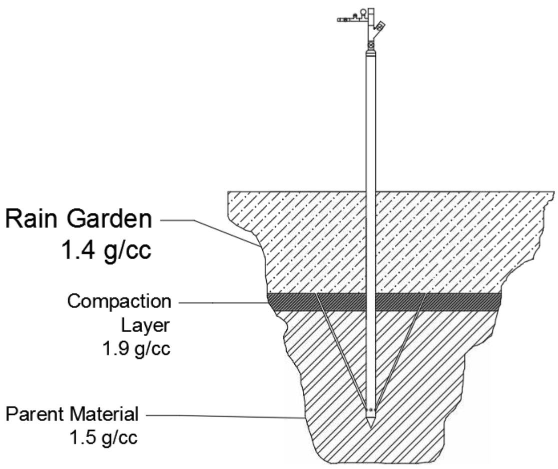

Figure 19: Rain garden cross section after treatment. The pole extends beyond the compaction layers which formed as the result of repeated stress and at the interface of high permeability substrate in the rain garden and low permeability parent material beneath. Fractures created by injection device extend at a 24 degree angle towards the surface, breaking through the compaction layer and diffusing into the porous organic substrate of the rain garden. Calculations for the predicted angle of 34.5 degrees are available in Appendix A.6.

5.2 PROTOTYPE

The prototype was built from galvanized steel tubing with a 1.5 inner diameter. Male NPT threads were added to the ends of each of the 4- and 6-foot lengths of tubing. The six-foot length had four $\frac{5}{16}$-inch holes drilled 90 degrees from each other at a 3 inch distance from the bottom threads whereon a standard end cap was attached. The top of the tube was fit with a 1.5-inch to $\frac{3}{4}$-inch adapter attached to the connection fittings as shown in figure 11. An accumulator was constructed from the remaining 4 foot length of tubing and attached to the top. This enables the storage and further pressurization of air that can be instantaneously released at higher flow rates to the soil.

5.3 TESTING METHODOLOGY

Tests were performed on a 1.44 g/cm^3 clay type soil that had been compacted in preparation by a sheepsfoot roller. A 1.25-inch pilot hole was bored into the ground using a hand driven bucket auger to a depth of 40 inches. The 1.68-inch outer diameter pipe was then inserted into the soil using a hand-held fence post driver until it reached the base of the bore hole. Half a gallon of 50 % biochar mixture was poured into the tube before attaching the accumulator and pneumatic connections to the top. This accumulator size is only 66 % of the .55 gallons of proppant and fluid being injected. The final accumulator design should have at least 133 % the volume of the rod to ensure that the pressure remains above 100 psi at the pipe for the duration of the injection to account for the pressure drop along the length of the fracture. After the accumulator had equilibrated to a pressure of 125 psi, the air supply was closed, and the ball valve connecting the accumulator to the injection tube was opened rapidly. Within 5 seconds, the proppant filled fluid exited the tube, and the ground visibly fractured at a radius of 17 inches around the tube.

5.3.1 PRELIMINARY RESULTS

Figure 20: Approximately 5 seconds after injecting 0.5 Gallons of proppant mixture at 125 psi, the perimeter of the cone highlighted above showed fractures around the edges. The area enclosed by the circle appeared to raise intact and rested at a higher position after the injection.

.

Figure 21: A fracture was measured exiting the surface of the ground 17 inches from the center of the pole.

6 CONCLUSION

After analyzing historical designs of devices seeking to fracture the soil, such as the Terralift and the Soil Shaker 2000, as well as other possible approaches such as using a subsoiler, soil amendment, or soil drilling, the Infiltration Team decided upon a pneumatic soil fracturing system which delivers compressed air, biochar, and water into the soil to induce fractures.

The manual, tube-driven system was chosen to enable remediation of failing rain gardens with swampy ground which does not allow for the use of heavy machinery. Compressed air forces the biochar and water out of the tube and into the induced soil fractures.

A prototype was tested which demonstrated that such a pneumatic system is able to induce soil fractures. The size of these fractures is unknown however, as well as the increase in infiltration which would result from these fractures. Further testing in partnership with soil scientists is needed in order to perform a fracture mapping analysis which will determine the size of the fractures. This pore size distribution analysis will then be related to an increase in infiltration.

Further testing on different soil types is also needed to determine how soil strength varies as soil type changes. It must be tested whether the Mansaver is able to overcome soil resistance encountered in these different soil types.

It must also be determined how much force is needed to remove the tube with different tip sizes. The tip size must be tested to see how changing tip size will affect how well the tube is able to be sealed by the soil. It is possible that a separate sealing structure may be necessary.

However it is certain from prototype testing that fractures can be induced from compressed air delivered into the soil. These fractures will intrinsically increase permeability because of the high permeability of biochar which is added to the soil.

A APPENDIX

A.1 TUBE CALCULATIONS

A.1.1 INSERTION

A common method of estimating the resistance is using a penetrometer. A sample of penetration resistance vs soil depth is given in Figure 13 below. Although this method is good for spot measuring, it can vary greatly over short distances. [25]

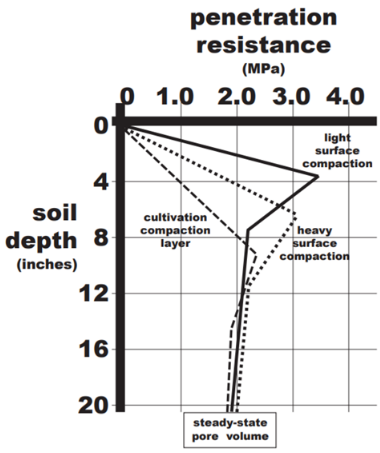

Figure 22: Common Penetration Resistances. A maximum pressure of 3 MPa is seen in heavily compacted soils.

The shear stress of the soil is governed by the following equation

$$\tau = c' + \sigma' tan\phi' \tag{3}$$

where,

τ = soil strength

c' = apparent cohesion

σ' = normal stress

ϕ' = angle of internal friction

The force required to press the tube depends on many constantly changing factors such as bulk density, degree of compaction, and soil texture. These factors can make two insertion sites a mere few feet from each other vary drastically in penetration resistance. Because of the uncertainty associated with soil properties and because this device is designed for versatility in a wide variety of locations, there is no specific universal value for soil strength. However, multiple penetrometer tests may be conducted in a certain region to get a general idea of soil strength. Therefore we are using an averaged maximum value found during research. A good maximum value for soil strength for compacted clayey soils is 10 psi.

Our tube acts as a slender pile. For slender piles, the vast majority of the shear stress comes from the sides of the pile interacting with the soil around it. According to Principles of Foundation Engineering 5th Edition, the downward force is approximately equal to the friction force resisting it. To find the force at which the soil will resist tube penetration, we must multiply the soil strength by the surface area of the rod submerged under the ground. [6]

$$surface\ area = \pi(d)(L) = 3.14(1.66in)(4ft)(\frac{12in}{1ft}) = 250in^2 \tag{4}$$

where,

d = diameter

L = length submerged

$$soil\ resistive\ force = \tau(surface\ area) = (10psi)(250in^2) = 2500lb \tag{5}$$

where,

τ = soil strength (psi)

This shows that the Mansaver must be able to overcome at least 2500 lbs force to insert the tube into the ground.

The following lists the manufacturer's specifications for the Mansaver:

Pressure = 70 psi

Flowrate = 2.5 cfm

Kinetic energy = 2872 lb-ft

Length = 25 in

Weight = 32 lbs

Strokes per minute = 80-85

To determine whether the kinetic energy of 2872 lb-ft applied to the collar of the Mansaver will be sufficient to overcome the 2500 lbs of resistive force from the soil, the following work-energy equations were used.

$$kinetic\ energy\ (KE) = \frac{1}{2}mv^2 \tag{6}$$

where,

m = mass

v = velocity

For an impact, the work exerted by an impact force slowing down a moving object equals the work done by a spring force. [24]

$$W = \frac{1}{2}F_{max}(s) \tag{7}$$

where,

W = work

F = force

s = deformation distance

On the pneumatic hammer's impact with the tube, all the kinetic energy will be converted into work and the above equations can be combined.

$$\frac{1}{2}F_{max}(s) = \frac{1}{2}mv^2 \tag{8}$$

Rearranging for Fmax

$$F_{max} = \frac{mv^2}{s} \tag{9}$$

The deformation distance, s, is the distance that the tube will travel into the ground upon impact with the pneumatic hammer. This distance depends on many soil characteristics such as texture, degree of compaction, and moisture content. Suppose that the tube travels 3 inches into the soil.

$$F_{max} = \frac{mv^2}{s} = \frac{(2872ft-lb)(2)}{3in}(\frac{12in}{1ft}) = 23,000lbs \tag{10}$$

This force greatly over and above the resistive force of the soil indicates that the Mansaver will be able to insert the tube into the soil. If the Mansaver meets an impervious object such as a large slab of rock, it is believed that the Mansaver will simply bounce back up because it does not have infinite mass and is therefore not able to deliver extremely large forces. Therefore the tube stress concentrations were examined using the method of impact loading described in Section 7.3.2

A.1.2 REMOVAL

The 8 Ton capacity of the Xtremepower US Long Ram Jack is much larger than the soil strength calculated in section A.1.1. Therefore there is little doubt that the Long Ram Jack will be able to lift the tube. The dimensions of the collar attachment were determined using the following stress analysis.

$$\sigma_b = \frac{M}{Z} \tag{11}$$

where: M = moment, Z = section modulus

For a rectangular cross section: [9]

$$Z = \frac{bd^2}{6} \tag{12}$$

where: b = length, d = height

$$\sigma_b = \frac{M}{Z} = \frac{(2500lb)(4in)}{\frac{(2in)(2in)^2}{6}} = 7500lb \tag{13}$$

The moment was found assuming the soil strength calculated in A.1.1. and the distance from the bottle jack to the tube.

$$FS = \frac{\sigma_{yield}}{\sigma_{working}} = \frac{36,000psi}{7500psi} = 4.8 \tag{14}$$

This large factor of safety is necessary because of the uncertainty accompanying the calculations for soils strength in A.1.1.

A.2 TUBE ANALYSIS

A.2.1 STRESS CONCENTRATION

The injection tube used in this design will require holes to be drilled due to the need for injecting a fluid at a desired pressure. These holes create a concentration of stress at specific points on the material. This leads to a concern of the holes being forced close due to the axial loading on the tube. Equation (15) provides the stress concentration factor for a tube with a transverse circular hole [21].

$$K_t = C_1 + C_2(\frac{2r}{D}) + C_3(\frac{2r}{D})^2 \tag{15}$$

where,

K_t = Stress Concentration Factor

C_1 = 3.0

C_2 = 0.427 - 6.770($\frac{d}{D}$) + 22.698($\frac{d}{D}$)^2 - 16.670($\frac{d}{D}$)^3

C_3= 11.357 + 15.665($\frac{d}{D}$) - 60.929($\frac{d}{D}$)^2 + 41.501($\frac{d}{D}$)^3

d = Inner Diameter (in.)

D = Outer Diameter (in.)

r = Radius of Hole (in.)

Using an inner diameter of 1.278-in. and an outer diameter of 1.66-in.: C_2 and C_3 were found to be 1.06 and 6.24 respectively. Using these values along with the hole diameter of 0.3125 in., the stress concentration factor of 3.42 was determined for this design.

$$K_t = 3.0 + 1.06(\frac{2(0.156in.)}{1.66in.}) + 6.24(\frac{2(0.156in.)}{1.66in.})^2$$

$$K_t = 3.42$$

A.2.2 IMPACT LOADING

The tube will be inserted into the ground in a completely vertical direction, meaning only the vertical force and reaction need to be considered for the peak stress calculations as shown in figure 23.

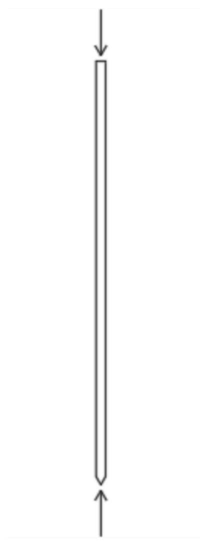

Figure 23: Free Body Diagram of injection tube used for peak stress calculations. Rod is in static loading summing forces to 0.

During insertion, the tube will be under an impact loading caused by the Mansaver pneumatic post driver. To analyze this impact loading, the maximum force that is expected to be resisted by the soil (2,500-lbs.) is multiplied by a factor of two to get a maximum force for analysis. This maximum force of 5,000-lbs. appears in the free body diagram in figure 23. Using the equation for peak stress (16) based on a stress concentration factor and a force over a cross sectional area, a peak stress of 19,400-psi was found.

$$\sigma_{peak} = K_t(\frac{4F}{\pi(D^2 - d^2)}) \tag{16}$$

where,

σ_{peak} = Peak Stress, (psi)

K_t = Stress Concentration Factor

F = Load (lbf)

D = Outer Diameter (in.)

d = Inner Diameter (in.)

$$\sigma_{peak} = 3.42(\frac{4(5,000lbf)}{\pi((1.66in.)^2 - (1.278in.)^2)})$$

$$\sigma_{peak} = 19,400psi$$

When comparing the peak stress previously calculated with the yield stress of A500 steel, which is 42-ksi, a factor of safety of 2.16 exists with this analysis.

A.2.3 THICK-WALLED PRESSURE VESSEL

When injection is occurring, the internal pressure of the tube is expected to reach a maximum of 130 psig. The pressure outside of the tube is dependent on the soil conditions and depth, however an expected pressure of 50 psig will be used for this scenario. The tube's outer diameter to inner diameter ratio classify it as a thick-walled pressure vessel. Equations (17), (18), and (19) represent the longitudinal, radial, and tangential stresses for a thick walled cylinder respectively [3].

$$\sigma_l = \frac{P_i a^2 - P_o b^2}{b^2 - a^2} \tag{17}$$

$$\sigma_r = \frac{P_i a^2}{b^2 - a^2}(1 - \frac{b^2}{r^2}) \tag{18}$$

$$\sigma_r = \frac{P_i a^2}{b^2 - a^2}(1 + \frac{b^2}{r^2}) \tag{19}$$

where,

σ_l = Longitudinal Stress, (psi)

σ_r = Radial Stress, (psi)

σ_t = Tangential Stress, (psi)

P_i = Internal Pressure, (psi)

P_o = Outer Pressure, (psi)

a = Inner Radius (in.)

b = Outer Radius (in.)

r = Radius to Point in Question (in.)

Using Equation (17): longitudinal stress at any point with 50 psig external pressure was calculated to be 40 psi.

$$\sigma_l = \frac{130psi(0.639in)^2 - 50psi(0.88in)^2}{(0.88in)^2 - (0.639in)^2}$$

$$\sigma_l = 40psi$$

Using Equation (18): the max radial stress, occurring at the inner surface, was calculated to have a magnitude of 130 psi.

$$\sigma_r = \frac{130psi(0.639in)^2}{(0.88in)^2 - (0.639in)^2}(1 - \frac{(0.88in)^2}{(0.639in)^2})$$

$$\sigma_r = -130psi$$

Using Equation (18): the max tangential stress, occurring at the inner surface, was calculated to have a magnitude of 420 psi.

$$\sigma_t = \frac{130psi(0.639in)^2}{(0.88in)^2 - (0.639in)^2}(1 + \frac{(0.88in)^2}{(0.639in)^2})$$

$$\sigma_r = 420psi$$

If the max stress due to the internal pressure, tangential stress, is multiplied by the stress concentration factor, a peak stress of 1,436-psi occurs. This peak stress due to internal pressure provides a factor of safety equal to 29.2 in this loading scenario.

A.2.4 BUCKLING LOAD

The load required to buckle the rod was a concern due to applying an axial load at each end of the long rod. Equation (20) can be used to calculate the critical buckling load of a column with both ends fixed [1].

$$P_{critical} = \frac{\pi^2 E I_{min}}{(0.5L)^2} \tag{20}$$

where

$P_{critical}$ = Critical Buckling Load, (lbf)

E = Modulus of Elasticity, (psi)

I_{min} = Smallest Moment of Inertia of Cross Section, (in^4)

L = Column Length Between Ends, (in)

Using Equation (20) with a length of 72-in., a Modulus of Elasticity of 29x10^6 psi, and a Moment of Inertia equal to 0.231 in^4: the critical buckling load was found to be 43,470 lbf.

$$P_{critical} = \frac{\pi^2 (29x10^6 psi)(0.231 in^4)}{(0.5(72in))^2}$$

$$P_{critical} = 43,470lbf$$

This force of 43,470 lbf is substantially larger than the maximum expected force of 2,500 lbf multiplied by 2, meaning buckling of the rod will not occur.

A.2.5 FLUID FLOW

There is the potential in this design for fluid flow to leak along the length of the tube and exit through an annular section at the surface. Due to this concern, it is desired that the orifices at the bottom of the tube be able to deliver more flow than the estimated leakage. The leakage along the length of the pipe was estimated by modifying the orifice equation to fit an annular section, Equation (21).

$$Q = C_d \frac{\pi(d_o^2 - d_i^2)}{4} \sqrt{2gh} \tag{21}$$

where,

Q = Peak Discharge, (ft^3/s)

C_d = Coefficient of Discharge = 0.61

d_o = Outer Diameter of Annular Section, (ft)

d_i = Inner diameter of Annular Section, (ft)

g = Acceleration from Gravity = 32.2 ft/s^2

h = Head Acting on Center Line (ft)

By using Equation (21) with the assumption that the largest difference in inner and outer diameter for the annular section will be 1-mm., a leakage of 17.04 gpm was found.

$$Q = 0.61\frac{\pi((0.138ft + 0.0394ft)^2 - (0.138ft)^2)}{4}\sqrt{2(32.2\frac{ft}{s^2})(50psi)(\frac{2.31ft}{1psi}}$$

$$Q = 0.61(0.00072ft^2)(86.24\frac{ft}{s})$$

$$Q = 0.034\frac{ft^3}{s} = 17.04gpm$$

The flow delivered by the holes at the bottom of the tube was determined using the orifice equation, Equation (22).

$$Q = C_d A\sqrt{2gh} \tag{22}$$

where,

Q = Peak Discharge, (ft^3/s)

C_d = Coefficient of Discharge = 0.61

A = Area of Orifice, (ft^2)

g = Acceleration from Gravity = 32.2 ft/s^2

h = Head Acting on Center Line (ft)

The system is planned to operate at 100 psig internal pressure with the external pressure being dependent on the soil conditions and injection depth. For these calculations, this external pressure will be assumed to be 50- psig. The total orifice area in this scenario is equal to the total area of the four holes sized to be 5/16 in. diameter.

$$Q = 0.61(4)(\frac{\pi(\frac{5}{16}in(\frac{1ft}{12in}))^2}{4}\sqrt{2(32.2\frac{ft}{s^2})(100psi - 50psi)(\frac{2.31ft}{1psi}}$$

$$Q = 0.61(4)(0.00053ft^2)(86.24\frac{ft}{s})$$

$$Q = 0.111\frac{ft^3}{s} = 49.82gpm$$

The holes at the bottom of the tube are able to deliver more fluid flow than the amount that can leak to the surface along the tube. This allows for a build up of pressure at the bottom of the tube that will be used to fracture the soil.

A.3 COMPRESSOR CALCULATIONS

A.3.1 PRESSURE DROP CALCULATIONS

The expected pressure drop across the pneumatic hose assuming 100 ft of hose is calculated below. The general expression for pressure drop is:

$$\Delta p = \lambda \rho \frac{v^2}{2} \frac{L}{D} \tag{23}$$

where,

Δp = Pressure Drop, (lb/ft^2)

λ = Dimensionless Friction Coefficient

ρ = Fluid Density, (lb/ft^3)

v = Average Flow Velocity, (ft/s)

L = Length of Pipe, (ft)

D = Inner Diameter of Pipe, (ft)

The average flow velocity, v, is approximated with the following expression:

$$Q = vA \tag{24}$$

where,

Q = Volumetric Flow Rate, (ft^3/s)

v = Average Flow Velocity, (ft/s)

A = Cross-Sectional Area of Pipe, (ft^2)

The cross sectional area for the pipe is simply:

$$A = \frac{\pi D^2}{4} \tag{25}$$

where,

A = Cross-Sectional Area of Pipe, (ft^2)

D = Diameter of Pipe, (ft)

$$A = \frac{\pi((0.5in)\frac{1ft}{12in})^2}{4}$$

$$A = 0.00136ft^2$$

Average flow velocity is then calculated:

$$v = \frac{Q}{A}$$

$$v = \frac{(15\frac{ft^3}{min})\frac{1min}{60s}}{0.00136ft^2}$$

$$v = 183.8\frac{ft}{s}$$

In order to calculate the dimensionless friction coefficient, λ, a calculation for Reynolds number is required. The following general equation will be used:

$$Re = \frac{4\rho Q}{\pi D \mu} \tag{26}$$

where,

Re = Reynolds Number, (dimensionless)

ρ = Fluid Density, (lb/ft^3)

Q = Volumetric Flow Rate, (ft^3/s)

D = Inner Diameter of Pipe, (ft)

μ = Fluid Viscosity ($\frac{lbs}{ft^2}$)

The dynamic viscosity of air at an elevation of 5,000 ft is 3.637*10-7 lbs/ft^2. The density of air is 0.0765 lb/ft^3.

$$Re = \frac{4(0.0765\frac{lb}{ft^3})(15\frac{ft^3}{min})}{\pi((0.5in)\frac{1ft}{12in})(3.637 * 10^{-7}\frac{lbs}{ft^2})}$$
$$Re = 6,000,000$$

The general expression for calculating the friction coefficient is:

$$\lambda = \frac{1}{(2log(0.5625Re^{\frac{7}{8}}) - 0.8)^2}$$
$$\lambda = \frac{1}{(2log(0.5625(6,000,000)^{\frac{7}{8}}) - 0.8)^2}$$
$$\lambda = 0.009$$

The pressure loss in the hose can now be calculated.

$$\Delta p = \lambda\rho\frac{v^2}{2}\frac{L}{D}$$
$$\Delta p = (0.009)(0.0765\frac{lb}{ft^3})(\frac{(183.8\frac{ft}{s})^2}{2})(\frac{100ft}{(0.5in)\frac{1ft}{12in}})$$
$$\Delta p = 6psi$$

An approximate pressure loss of 6 psi is expected in a system delivering a flow rate of 15 cfm through 100 ft of hose.

A.3.2 PNEUMATIC CIRCUIT DIAGRAM

A diagram detailing the conceptual layout of the compressed air system is provided:

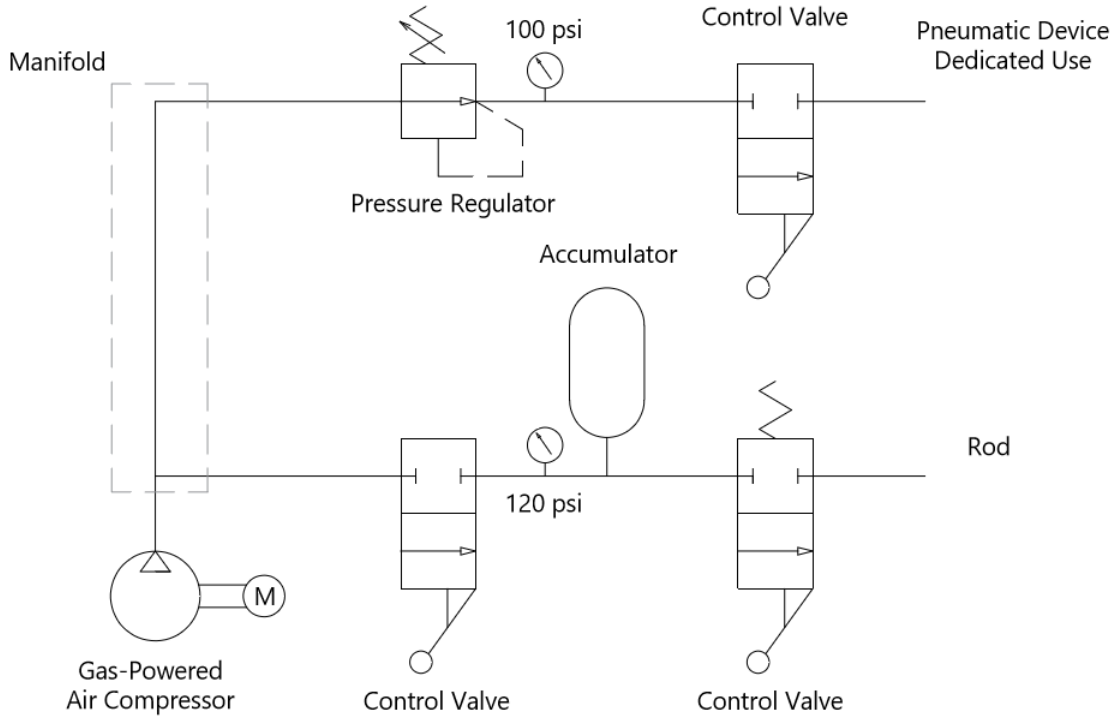

Figure 24: A pneumatic circuit diagram detailing the main components of the compressed air system is shown.

A.4 PROPPANT CALCULATIONS

A.4.1 ACCUMULATOR CALCULATIONS

Since the pressure at the tip of the fracture will drop as the distance from the fracture tip to the injection rod increases, an accumulator volume will be selected such that the pressure at the rod maintains 100 for the duration of the injection. Given a starting pressure of 130 psi maximum pressure from the single stage compressor, the required accumulator volume would be 1.3 times that of the rod volume to ensure that 100 psi is still available as the last of the proppant fluid leaves exits the injection rod.

A.4.2 ACCUMULATOR CALCULATION

The void space for a 1.5-inch ID pipe is 0.55 gallons, and the minimum pressure at the base hole desired was assumed to be 100 psi. The percentage of pressure drop between the initial value of 125 psi and a final value of 100 psi was 20 . The required volume of the accumulator was assumed to be 125 % of total tube volume.

$$0.55\ gallons\ in\ tube * 1.25 = 0.59\ gallons\ in\ accumulator$$

Using the flow rate of $15cfm * .13\frac{gpm}{cfm} = 2gpm$. This means that it would take 17 seconds to fill up the accumulator fully as shown below.

$$\frac{0.59\ gallons\ in\ accumulator}{2\ gpm} = 0.3minutes 0.3minutes * 60\frac{s}{min} = 17seconds$$

A.4.3 PROPPANT DISTRIBUTION

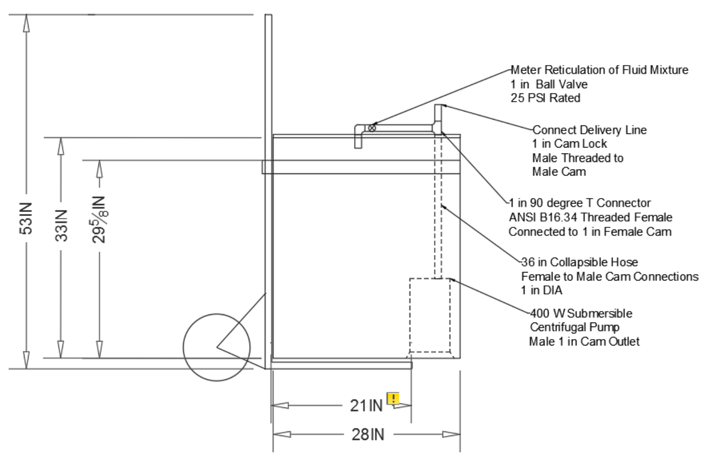

Figure 25: An initial conception of a way to distribute the proppant to the injection tube. Since mixing was found to be ineffective and the 500 pounds of proppant mixture would be unwieldy, this approach was discarded.

During experimentation, it was found that by soak the proppant and fluid together in preparation, the mixture becomes more predictable in its dosage rate and the system becomes less complex overall since the properties of biochar can be more easily anticipated.

A.5 SOIL CONSISTANCE

Soil Consistance is defined as “the resistance of a soil at various moisture contents to mechanical stresses or manipulation”combining cohesion and adhesion.[6] Adhesion is defined as the molecular attraction of two substances, ie. water and soil or biochar and pollutants. Cohesion is the force holding solid or liquid to itself, this force decreases with a rise in temperature. Consolidated and compacted clay soils experience a higher cohesive force than uncompacted clay soils. Rupture resistance is a measure of the strength of the soil to withstand applied stress and is closely related to soil consistence. Other properties of soil include stickiness and plasticity. Stickiness is the ability of soil to adhere to other objects physically at a larger scale than adhesion, this is determined by the moisture content at which clay between the forefinger and thumb have maximum adherence. Plasticity is the degree to which the soil can deform without rupture. Soils with clay content over 15% exhibit plasticity.

A.5.1 MOIST CONDITIONS

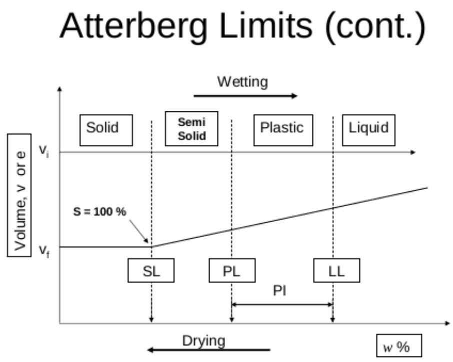

Figure 26: Atterberg limits are important in defining the consistency of fine grained soils and divide the soils along 4 states - solid, semi-solid, plastic, liquid.

Liquid Limit (LL) is defined as the moisture content at which soil begins to behave as a liquid material and begins to flow(Liquid limit of a fine-grained soil gives the moisture content at which the shear strength of the soil is approximately 2.5kN/m 2) In the lab, the LL is defined as the moisture content (%) required to close a 2-mm wide groove in a soil pat a distance of 0.5 in along the bottom of the groove after 25 blows. The ASTM D 4318 defines the soil sample size as 150g of soil passing # 40 sieve using a casagrande liquid limit device.

Plastic Limit (PL) is defined as the moisture content at which soil begins to behave as a plastic material. Plasticity Index (PI) is the difference between the liquid limit and plastic limit of a soil

Shrinkage Limit (SL) is defined as the moisture content at which no further volume change occurs with further reduction in moisture content.

The effects of moisture on biochar were also researched. Initially it was unclear how biochar between 1 and 2 mm would react to water, after testing this in the soil science laboratory and during a prototype injection it became clear that if the biochar was allowed to soak for 24 hours it would absorb water. Another concern with using biochar was that the repeated hydration and dehydration cycles that occur in the soil would cause the substrate to shrink and swell. This would cause substrate losses over time and could be a problem. Upon further research, biochar has been found to only swell during the initial hydration and that biochar will not repeatedly shrink and swell during hydration cycles. [26]

A.6 FRACTURE CALCULATIONS

The fracture angle of the soil is dependant on the frictional angle, which is a property of soil type. From tables, the internal frictional angle ϕ' is about 22.5 ° for normally consolidated clay soil and up to 26.5 ° for compressed clay.

$$\begin{aligned} \theta_{fracture} &= 90 - (45 + (\phi'/2)) \\ \theta_{fracture,clay} &= 34.5^\circ \\ \theta_{fracture,compressed\ clay} &= 32^\circ \end{aligned} \tag{27}$$

A.6.1 FLUID REQUIREMENTS

The viscosity of the fluid is dependant upon the diameter and density of the proppant chosen as shown below in stokes equation. It is estimated that a 1.15 MPa per second viscosity would be needed for sand compared to a 1.05 MPa viscosity for biochar to achieve the same 25 second settling time. A jar test could be used to easily compare different proppants at different viscosity and therefore adjustments can be made by altering the viscosity of the fluid in the field if necessary, however, the addition of a viscosity enhancer was found to be unnecessary during initial biochar injection testing. The overall size of the reservoir required to hold the proppant before injection will be dependant on the maximum treatment size area and the pattern of injection required to create a sufficient infiltration increase. Expected treatment area is estimated to be about 10,000 square feet, but currently the infiltration pattern is unknown.

Stokes equation (28) describes the relationship between the velocity that a particle rises or falls when suspended in fluid

$$v = \frac{d^2(\sigma_s - \sigma_o)g}{18\eta_o} \tag{28}$$

Sand offers three major trade-offs since it is a high density proppant. First, using higher density materials means smaller fracture volume for a fixed weight of proppant. Second, higher density material means higher cost. Third, a higher density material will have faster settling rate in the carrier fluids. To prevent settling, the common practice is to use high viscosity fracturing fluids to keep the proppant material suspended to allow it to penetrate further into the fractures. Further complicating the use of sand, viscosity additives must be removed with an enzyme that is combined in the fluid to prevent clogging. [10]

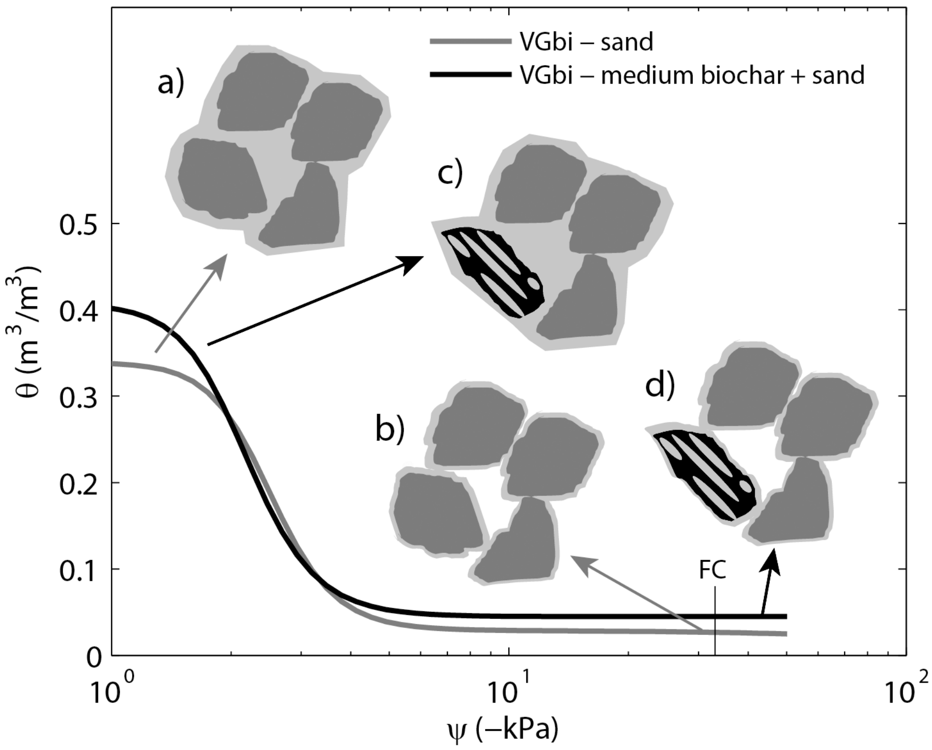

Figure 27: Pore Shape and Water Rentention Curve for biochar and sand. Biochar adds pore space and increases storage compared to denser sand particles.[26]

A.6.2 PROPPANT INJECTION VOLUME REQUIREMENT CALCULATIONS

To find the maximum volume of proppant required, the treatment area needs to be estimated for a fracture running the full 4 feet depth. Using the model included in the appendix, the angle of friction for treating 4 feet of compaction under 4 feet of porous rain garden depth was calculated to be 34.5°. This means that the fractures will occur at a 34.5° angle off of the vertical plane, creating a cone that encompasses a 27 ft^3 volume.

A maximum volume was initially estimated by using difference in bulk densities before and after the treatment as shown in the following equation:

$$V_{max} = \frac{bulk\ density_{initial} - bulk\ density_{final}}{bulk\ density_{maximum}} \tag{29}$$

Equation 29 yielded about 1.7 ft^3 of volume change for the treated area or about 6% of the total volume. The infiltration increase due to pore side distribution change at a 5% biochar addition to clay soil is approximately a 2x factor increase. The performance criteria of our design requests at least an order of magnitude of increase in infiltration which would require a 20% biochar addition if we rely on particle size distribution changes alone. 20% of 27 ft^3 is 5 ft^3 per injection, which is not a reasonable amount of media since it would require 3 ft^3 of soil be displaced. Therefore, our design will need to rely on creating maximizing the diameter of the fractures and the pore size within the fractures.

Estimating fracture size based on number of holes is a more realistic calculation. The equations below are in reference to the size of the fractures and are based on the fact that our injection tube has 4 holes of a 0.3 in diameter which will divide the flow of fluid before the fractures occur and the fracture angle is estimated at 34.5°. The failure angle comes from a mohr's circle analysis of the soils failure envelope for clay loam soils at a 4 foot depth.

For retroactively treating a rain garden, however, soil amendment is not really possible with out removing the garden first. The depth of an average rain garden was assumed to be 18 inches for these calculations, leaving a remaining 22 inch treated depth below that which can be treated with a 4 foot injection depth. It is assumed that the top 18 inches are too porous to fracture at the injection speed we are using, therefore only the 22 inch depth for the volume requirement calculations below.

Beginning with the length and area of each fracture formed at the size of the orifice on the nozzle the volume of each fracture is found.

$$\begin{aligned}
Length_{fracture} &= depth * sec(\theta_{fracture}) \\
&= 1.83 ft sec(34.5°) ft \\
Length_{fracture} &= 2.22 ft \\
V_{fracture} &= V_{outer\ cone} - V_{inner\ cone} \\
&= \pi \frac{h}{3}(r^2_{outer} - r^2_{inner}) \\
&= \pi \frac{h}{3}(r^2_{outer} - r^2_{inner}) \\
&= \pi \frac{1.83 ft}{3}(2.03 ft)^2 - (1.46 ft)^2 * 7.48 \frac{gal}{ft^3} \\
V_{fracture} &= 0.42 gallons
\end{aligned} \tag{30}$$

The total volume of a complete fracture was modeled as the annulus of 2 cones at the base of a rain garden with a compaction depth of 22 inches. These cones were assumed to have a need a fracture width of 0.2 inches, using an outer cone of a radius 17.2 inches and an inner radius of 17 inches. Volume of the combined fractures is found to be 0.42 gallons which will fit within the volume of the rod as shown below.

$$\begin{aligned}
V_{rod} &= \frac{\pi}{4} * d^2 * L \\
&= \frac{\pi}{4} * 1.5^2\ in^2 * 72\ in * \frac{ft^3}{12^3\ in^3} \\
&= 0.074\ ft^3 * \frac{7.48\ Gallons}{ft^3} \\
V_{rod} &= 0.55\ Gallons
\end{aligned} \tag{31}$$

Since this design relies on fracture diameter and not completely adjusting the particle size distribution of the soil, the 0.16 ft^3 volume within the 1.2 inch inner diameter injection tube was found to be sufficient since it allows for about 0.23 gallons of proppant fluid mixture to be injected per blast using the tube alone. A half gallon of proppant is the same volume of proppant used in the terralift or grow gun systems. The rod can be filled up with up to 7 gallons of mixture and can

Figure 28: Semi-open Impeller. The semi-open design offers increased rigidity and strength for pumping solids.

Figure 29: Delivery Pump. A submersible pump capable of pumping solids and stringy materials at rate of 15 GPM at 15 psi.

be injected multiple times within the same fracture location to inject more proppant into the same location if that is found to increase infiltration during further experimentation with this design.

A.6.3 PROPPANT DISTRIBUTION COMPONENTS

This proppant delivery system was considered during the design process. It is a secondary option to the hand delivery system that has been implemented that aims to automate the transport of the proppant mixture from the trailer to the injection rod. Although this system would automate a small part of the injection process, it was considered too complex to justify the time that it saved.

. A 12 volt battery connected to a 400 watt inverter is contained in a waterproof NEMA certified box that attaches to the dolly with two 200 lbf magnets. The magnets allow the power system to move and to be dismounted when necessary, but to will generally stay attached firmly.

.

The battery chosen has 200 Ah and is deep cycle, allowing for 3 hours of continuous operation before a 50 % drain on the battery is reached. Since the pump will not always be on, this should be sufficient for a single 12 hour work day if you assume the pump is operating at full power 25 % of the time. It should be noted that this calculation excludes efficiency losses from the inverter.

$$\begin{aligned} Watt/Volt &= Amps \\ 400W/12V &= 33A \\ 100Ah/33A &= 3\ hours \end{aligned} \tag{32}$$

A 15 % recycled volume per minute ratio is usually expected to keep a mixture homogeneous. In this context, that would assume that the proppant has been pre-mixed and is fully saturated. When the proppant has not been premixed the flow rate would need to be much higher, therefore it is recommended that the proppant be premixed in the 55 gallon barrels overnight before the day

Figure 30: Inverter. A 400 watt continuous, 800 watt peak inverter from harbor freight is required to convert 12 V DC to 120 V AC to power the pump. The clip on connections seen in the picture would need to be replaced with a screw on type battery connector.

Figure 31: Hopper. A standard 55 gallon drum containing a delivery pump and a mixture of fluid and proppant will function as the reservoir for this system. Standard drums have a diameter of 22.5 inches and a height of 33.5 inches.

of application.

$$55\,Gallons * 0.15/minute = 8.3\,GPM \tag{33}$$

Bulk Density Of biochar at different conditions:

$$\begin{aligned} bulkdensitydry &= 0.60g/ml \\ bulkdensitywetinitial &= .8g/ml \\ bulkdensitywetsaturated &= 1.5g/ml \end{aligned} \tag{34}$$

After opening the high pressure connection, the operator can control the injection fluid flow at the right side of the figure above using a a $\frac{3}{4}$ inch ball valve which can be used to open, close, or partially opened limit the flow of the pumped fluid.

A high pressure rated ball valve controls the systems connection with the injection pipe and protects the system from the high pressures of injection. It is important that this valve be shut after the proppant has been loaded into the system.

A 50 foot heavy duty garden hose can't meet the original 10,000 square foot goal in the worst case scenario of a circle, which would have a radius of 56 ft. Therefore, 25 foot extension is included which will cover any edge cases where the hose needs to route around something while allowing the 50 foot hose to be used alone for most cases.

A 8 inch spring guard smooths out the radius of the fluid hose at both connections ensuring that kinks do not form and protecting the collapsible hose.

Two ball valves control the flow of fluid from the pump to the injection tube. The first valve is at the hopper and will determine the mixing rate. A second valve is at the injection tube and will determine the fill rate based off the opening of the valve and the flow of the mixing rate, this valve is only open when the tube is filling before injection occurs. If the fill level is allowed to fill past the top of the tube it may begin filling the air injection tube, for this reason there is an overfill valve that must remain open between the fluid delivery valve and the air connection.

REFERENCES

[1] Csu presentation, chapter 9: Column analysis and design. Accessed 11-2018.

[2] Pneumatic fracturing - environmental consulting. *Pneumatic Fracturing - Environmental Consulting*, 2018.

[3] K. Anta. Thick walled cylinders. Accessed 11-2018.

[4] ASTM. Compressive strength. 2018. Accessed 11-30-2018.

[5] Community and Environmental Defenses Services (CEDS). 2012. Accessed 12-2018.

[6] Braja M. Das. *Principles of Foundation Engineering - 5th Edition*. Brooks/Cole, 2004.

[7] J. Deacon. Sonoran desert. *SONORAN DESERT*, 2018.

[8] EPA. Environmental fracturing. 2018. Accessed 10-30-2018.

[9] Holbrook L. Horton Erik Oberg, Franklin D. Jones and Henry H. Ryffel. *Machinery's Handbook 30th Edition*. Industrial Press, 2016.

[10] Ghaithan A. Al-Muntasheri Frank F. Chang Leiming Li Feng Liang, Mohammed Sayed. A comprehensive review on proppant technologies. *Petroleum*, 2014.

[11] I. Hakansson and R. C. Reeder. Subsoil compaction by vehicles with high axle load–extent, persistence, and crop response. *Soil Tillage Research*, 1994.

[12] S.a. Krieg. Cone penetrometer demonstration standard startup review checklist. Sep 1998.

[13] Lehmann. Temperature effects on carbon recovery, cec, ph and surface area. *Front. Ecol. Environ.*, pages 381–387, 2007.

[14] Knoxville BMP Manual. 2003. Accessed 12-2018.

[15] Rohrer Manufacturing. Accessed 11-2018.

[16] David Moore. Essentials of fungal cell biology. *Fungal Biology in the Origin and Emergence of Life*, page 19–41, 2016.

[17] J.r. Nimmo. Porosity and pore size distribution. *Reference Module in Earth Systems and Environmental Sciences*, 2013.

[18] Jeff S. Piotrowski and Matthias C. Rillig. Succession of arbuscular mycorrhizal fungi: Patterns, causes, and considerations for organic agriculture. *Advances in Agronomy Advances in Agronomy Volume 97*, page 111–130, 2008.

[19] Tom Schröder, Mathieu Javaux, Jan Vanderborght, Bernd Körfgen, and Harry Vereecken. Effect of local soil hydraulic conductivity drop using a three-dimensional root water uptake model. *Vadose Zone Journal*, 7(3):1089, 2008.

[20] Kurt A Spokas. Review of the stability of biochar in soils: predictability of o:c molar ratios. *Carbon Management*, 1(2):289–303, 2010.

[21] C.M. Stewart. Utep presentation, chapter 6: Stress concentration. Accessed 11-2018.

[22] Lisa Stiffler. Accessed 12-2018.

[23] LISA STIFFLER. 2011. Accessed 12-2018.

[24] Engineering Toolbox. Accessed 11-2018.

[25] Z Tian Ju Liu T Rein Weida Gao, W Whalley. Succession of arbuscular mycorrhizal fungi: Patterns, causes, and considerations for organic agriculture. *Scientific Direct*, 2016.

[26] James Tsz Fung Wong, Zhongkui Chen, and Annie Yan Yan Wong. Effects of biochar on hydraulic conductivity of compacted kaolin clay. *Environmental Pollution*, 1994.

[27] James Tsz Fung Wong, Zhongkui Chen, Annie Yan Yan Wong, Charles Wang Wai Ng, and Ming Hung Wong. Effects of biochar on hydraulic conductivity of compacted kaolin clay. *Environmental Pollution*, 234:468–472, 2018.

[28] XtremepowerUS. Accessed 11-2018.

[29] Shenggao Lu Yutong Zong, Danping Chen. Impact of biochars on swell–shrinkage behavior, mechanical strength, and surface cracking of clayey soil. *J. Plant Nutr. Soil Sci.*, 2014.

[30] Xiaokai Zhang, Hailong Wang, Lizhi He, Kouping Lu, Ajit Sarmah, Jian-Wu Li, Nanthi Bolan, Jianchuan Pei, and Huagang Huang. Using biochar for remediation of soils contaminated with heavy metals and organic pollutants. *Environmental science and pollution research international*, 20, 04 2013.

[31] Caroline A. Masiello Zuolin Liu, Brandon Dugan. Biochar particle size, shape, and porosity act together to influence soil water properties. *PLOS one*, 2017.