THE DEVELOPMENT OF A LOW-COST, LEAD FREE WELLPOINT DRILLING SYSTEM FOR USE IN HOUSEHOLD WELL SYSTEMS IN COASTAL AREAS OF MADAGASCAR

by

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DEDICATION

I want to give praise and thanks to my Lord and Savior Jesus Christ through whom all things are possible (Philippians 4:13). Lord, thank you for the wisdom, courage and strength you have given me through this process.

I want to dedicate this thesis to my family without whose love and encouragement I would not be where I am today. Thank you Momma, Deddy, Mrs. Mary, Matt & BJ, Brian, Aunt Marilyn & Uncle Ollie.

Lastly, to all my friends and Mercer family, thank you for your encouragement and patience with me through this process, listening when I needed to vent. I am so blessed to have friends and family who care so much and are so encouraging.

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THE DEVELOPMENT OF A LOW-COST, LEAD FREE WELLPOINT DRILLING SYSTEM FOR USE IN HOUSEHOLD WELL SYSTEMS IN COASTAL AREAS OF MADAGASCAR

Under the direction of DR. MICHAEL F. MACCARTHY

In eastern Madagascar Pitcher Pump systems containing leaded components in the pump head and the drilled well are widely used. The ingestion of lead (Pb) in any form can be very harmful to humans. Previous research has measured lead in these systems, and recommended a way to eliminate the use of lead in the pump head. The purpose of the current study is to develop a cost-effective, lead-free alternative drilled well system. Three alternative methods, the Cased System, Exposed-Screen System A, and Exposed-Screen System B, were designed and tested. A total of nine wells were drilled over a span of two drilling phases at USF's GeoPark in Tampa, Florida. Of the three methods, the Exposed-Screen System B Method, a modification to Exposed-Screen System A, proved to be the most successful. It was also the simplest design, required the least amount of equipment, and was the most cost-effective. This method was modified for testing in Madagascar. Modifications were necessary to accommodate for material availability.

The newly developed method was called the Madagascar Exposed-Screen System. Two wells were successfully installed, removed, and examined using this method. Future recommendations include further research into specific materials to be used in drilling and additional testing in eastern Madagascar.

CHAPTER 1. INTRODUCTION TO THE STUDY

In eastern Madagascar it can be difficult and very expensive to gain access to publicly provided potable water (Akers et al., 2015). According to the United Nations Children's Fund (UNICEF), more than 80 percent of those living in Madagascar earn less than US$1.25 per day, and less than 34% of people living in rural areas of Madagascar have access to improved drinking water sources (2013). Additionally, the public water supply can be unreliable, and public utilities do not always have the necessary budget capacity to distribute water connections to all those who need them (United States Agency for International Development, 2010). JIRAMA, the national public utility that services 67 municipalities in Madagascar, suffers from operational inefficiencies and lacks the capacity to upgrade the aging infrastructure. This is partly due to high operating costs, setting very low water rates, and affordability issues among target customers (ibid., 2010).

In order to access an affordable and reliable water supply, many households in Madagascar have turned to self-supply. Self-supply is typically a development process in which a single family or group of families within a neighborhood invests in their own private water supply system. This water supply system is often delivered using low-cost technologies that can either extract shallow groundwater or collect rainwater (MacCarthy, Annis, & Mihelcic, 2013). Many households in coastal areas of Madagascar have had self-supply wells drilled and installed locally produced hand pumps (e.g., Pitcher Pumps) to meet their water needs. Unfortunately for users of these systems, there is a risk that they are consuming lead from the drinking water in these wells(Akers et al., 2015). In the coastal city of Tamatave, for instance, many local residents (estimated 170,000) have installed low-cost Pitcher Pump systems (MacCarthy, Annis, et al., 2013). Leaded components found in the pump head and well casing present significant health risks, as there is a high probability that these components are leaching lead into the water.

Children can be the most vulnerable to lead exposure (World Health Organization, 2011). There is no safe blood lead level for children, as exposure to lead in even small amounts has been linked to a wide array of harmful neurological and developmental effects (Wheeler et al., 2013). However, the World Health Organization (WHO) issued a 2011 guideline recommending no more than 10 ug/L in drinking water (WHO, 2011). In Tamatave, studies indicated that in households using a Pitcher Pump system, water samples were commonly above 10 ug/L (Akers et al., 2015; MacCarthy, Annis, et al., 2013). This represents the possibility of significant negative effects from exposure to lead in the drinking water.

The issue of leaded components in the Pitcher Pump has been recently studied by researchers at the University of South Florida (Akers et al., 2015; MacCarthy, Annis, et al., 2013). While identifying leaded valve weights as the primary source of contamination, and recommending that iron weights be used instead, the health risk from lead contamination from the leaded components being used in the casing of the drilled well remains. Specifically, the well screen, typically made of brass, can contain lead. In addition, the screen is attached to the well casing with lead-tin (Pb-Sn) solder (Akers et al., 2015). *Figure 1* shows a diagram of the leaded components in both the drilling system and the Pitcher Pump. When water comes into contact with these components, it is possible that the lead contained in them could contaminate the water supply through "electrochemical, geochemical, and hydraulic mechanisms" (Triantafyllidou & Edwards, 2012).

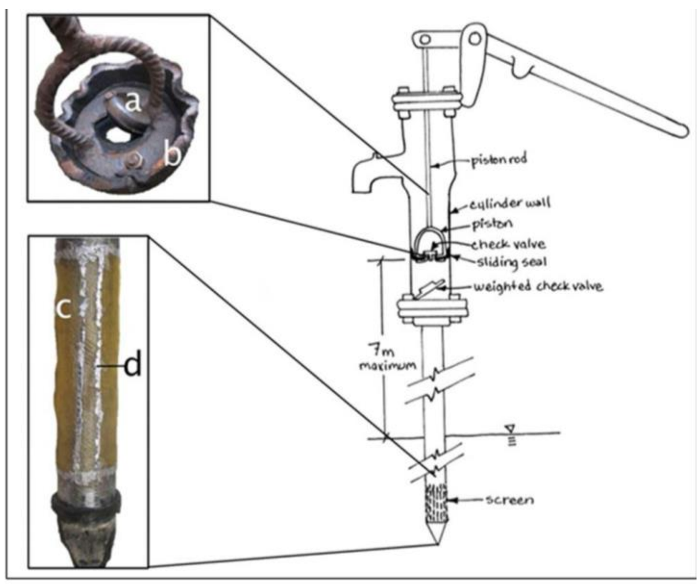

Figure 1. Diagram of Leaded Components in the Drive Point System (Akers et al., 2015)

Along with the replacement of lead valve weights from the pump, it would be beneficial to remove the lead-containing components from the well casing. The objectives of this study are:

1) to devise a well-point design (including materials and manual installation techniques) that eliminates the use of lead-containing components while maintaining the simplicity and cost-effectiveness of systems built locally in eastern Madagascar;

2) to assemble the components and tools for the selected well-point design option(s); and

3) to field test and assess the designed well-point installation to determine whether the new components and tools are a viable substitute for those currently in use.

The drilling options designed in this study, combined with the removal of leaded components in the Pitcher Pump system, could considerably improve the installation and use of the Pitcher Pump system. As the Pitcher Pump system is the most well-established, unsubsidized household hand pump system available in Madagascar, there is potential for an improved technology to spread throughout Madagascar and potentially to other countries (MacCarthy, Annis, et al., 2013).

CHAPTER 2. REVIEW OF RELATED LITERATURE

Water Scarcity in Africa

The importance of having reliable sources of potable water available to all people, worldwide, cannot be understated. It is universally understood that water is essential for life, and yet the WHO estimates that one of every three persons in the African Region suffers from scarcity of water (World Health Organization, 2015).

When water is scarce, hygiene may be poor. Bathing in or drinking contaminated water contributes to a startling array of diseases, such as diarrhea, dysentery, hepatitis A, typhoid and polio. Storage of water in households, often in open containers, invites mosquitos to breed and contributes to the spread of malaria (World Health Organization, 2014).

Water Deficits in Madagascar

Madagascar is an island country off the coast of East Africa with a population of just under 23 million. Less than 34 percent of those living in rural areas of Madagascar have access to safe drinking water (UNICEF, 2013). The government-owned water utility systems in Madagascar have been characterized as unpredictable, plagued by frequent shut-downs and contaminated water (Fajardo, n.d.).

Manual (Hand) Drilling Methods

In developing nations, manually drilled wells can provide people with water for agricultural and domestic use. Manually drilled wells can be found in South Asia, parts of Latin America, and parts of Africa, including Madagascar (Danert, 2009a). There are four sub-categories of manual drilling: augering, jetting, percussion and sludging.

Manual drilling can sometimes be more cost-effective and faster than conventional drilling (Wurzel, 2001). However, that depends on the location, technology being used, geology, hydrogeology, etc. Manual drilling methods are widely used in developing countries and can utilize machines to assist in drilling (Wurzel, 2001). Manual drilling can be attractive to small, local entrepreneurs, as the cost of this type of drilling is reasonable enough that local villages and groups of neighbors can pool their money to pay for the drilling themselves instead of looking to outside entities such as non-governmental organizations (NGOs) (Danert, 2009a). Such cooperation has the potential for high community involvement (Wurzel, 2001).

Cost Considerations

Conventionally drilled wells in sub-Saharan Africa can range in cost from US$2000-US$20,000 each, compared to manually drilled wells, which cost anywhere from US$20 to US$3000. The variability in cost can depend on the location and the type of technology used, as well as the geology and hydrogeology of the area (Danert, 2009b). In areas where the water table is not too deep, manual drilling offers major cost savings. Many well parts and tools needed for manual drilling can be locally manufactured, which makes them easier to purchase and less costly than machine drilling parts (Vuik, Koning, & Van der Wal, 2010). Manual drilling can be powered by human energy alone or supplemented from other sources, such as engines, to lift and drop the drilling tools. However, when manual drilling is powered solely by human energy, the amount of drilling that can be performed is limited to the amount of human energy that can be exerted. Also, certain geologic formations, where the soil is extremely hard or rocky, make conventional (or machine) drilling the favored choice (Danert, 2009a).

The Drive Point Method Defined

The drive point method, also known as the sand-point method, is one of the quickest, easiest, and most economical water well drilling techniques in the world. The drive point method is a type of percussion drilling that is widely used in both developing and developed countries. In developing countries, well-point drilling is known for ease of drilling and its cost-effectiveness (Peace Corps, 1982).

Drive point drilling dates back to 1100 B.C. in China and consists of driving a well-point into the ground (Vuik et al., 2010). Simply stated, a drive point or well-point is a piece of metal that has been fashioned into a point, usually attached with screws or solder to a screened pipe, and driven into the ground using a hammering device. Unlike other drilling methods, in the drive point method the soil is not excavated but is pushed to the side as the well-point is being driven into the ground. The drive point method cannot drill through hard formations (Koegel, 1985), but is effective at drilling through unconsolidated formations such as sandy soils (Mihelcic, et al. 2009). In many cases, this type of drilling can be done by one person in just a few hours, depending on the depth that is being drilled (A Laymen's Guide to Clean Water, 2015).

Materials Needed for a Drive Point System

Drive point wells generally include a well-point, sections of well pipe, a screen, couplings, and a drive cap. To attach extension pipes, special drive couplings are needed, which are larger than normal couplings and allow the pipe ends to butt together inside the coupling. This causes the driving force to be transmitted between pipes by the ends of the pipe instead of by the threads. A drive cap is used to protect the threads of the top pipe during the driving process (Koegel, 1985). The equipment needed also depends on the method of driving the well; however, driving equipment can generally be constructed from locally available scrap pipe and/or steel bars and standard pipe fittings. For less costly alternatives, there is PVC piping available in many countries. The thickness of PVC pipes being placed in the ground should always exceed 3 mm or the pipe could break when in use in deeper wells (Van der Wal, 2010).

Hammering Devices

Depending on the type of method used to drive the well, three common types of hammering devices are available. They are 1) the hand driver, a sliding weight that fits over the pipe being driven into the ground; 2) the internal driving bar (drive rod), which strikes the well-point directly; and 3) a sliding weight and drive stem, which attaches to the uppermost riser pipe coupling (Eberle & Persons, 1978). The design of basic drive hammers requires only basic metal working and blacksmith skills (Eberle & Persons, 1978). Metal piping is widely used during the driving process, because plastic and polyvinyl chloride (PVC) piping are not strong enough to withstand the stresses of being hammered into the ground (Peace Corps, 1982). However, PVC pipe can be used as well screens and riser pipe, through which the water flows into and is pumped out (Koegel, 1985).

Well Screens

The purpose of a well screen is to allow as much water and as few particles into the well as possible. In driven wells, they are attached near the bottom of the drive casing. Well screens must have the necessary strength to endure the forces of being driven into the ground and the abrasion of the materials which will pass through them. There are two common types of well screening for metal piping. The first is a perforated drive pipe fixed with a drive point. The perforated part of the pipe has a layer of brass screen of a desired fineness wrapped around it. The brass screen is then protected by another layer of perforated brass sheet that is wrapped around the brass screen. Both of these brass layers are soldered onto the pipe.

Unfortunately, there is a chance that brass screens can leach lead (Pb) into the water. In the United States, Wisconsin allows a lead content of up to 8 percent in the metal screens that are used to collect water in the wells (Wisconsin Department of Natural Resources, 2010). The Environmental Protection Agency (EPA) also requires that brass fittings and plumbing fixtures that are used in human water consumption can have no more than 8 percent lead content (Environmental Protection Agency, 2012).

A second type of screen is made by wrapping trapezoidal rods in a spiral around a set of round longitudinal rods placed in a circular pattern. All of the intersections are welded. This type of screen has a high percentage of open area and individual hole shapes that are not easily clogged (Koegel, 1985). Both screens are shown below:

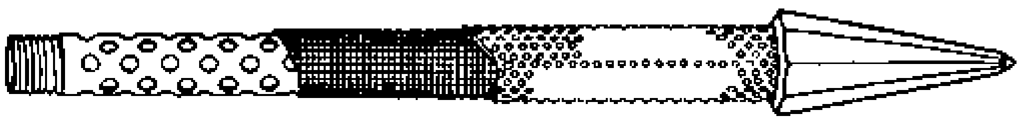

Figure 2. Perforated Pipe with Screen (Koegel, 1985)

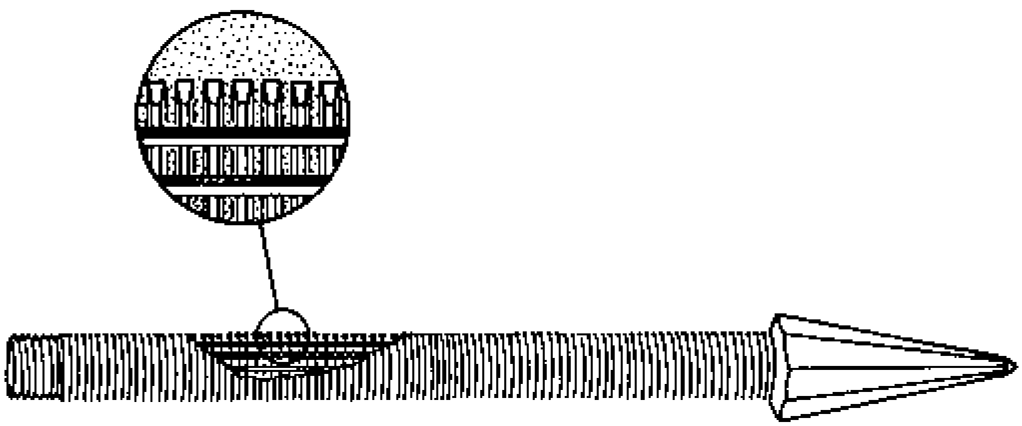

Figure 3. Spiral Trapezoidal Wire (Koegel, 1985)

A cheaper and lighter screen alternative is PVC. In some countries PVC pipe screens with pre-cut 1 mm slots can be purchased. When trying to save money on wells, the slots can be made by using a hacksaw (Van der Wal, 2010). Also a 100 percent polyester screen can be placed over the slots that were cut to help prevent sand from entering into the PVC pipe through the slots. The polyester screen will not decay when placed into the ground with the pipe (Buchner, 2010). The figure below shows how the slots can be made for a standard 4 in. pipe:

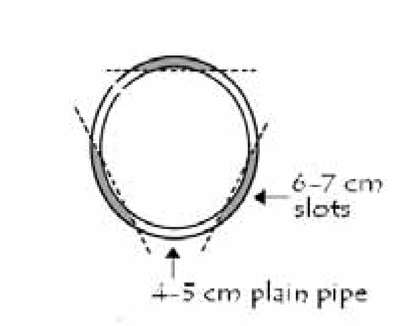

Figure 4. Slots in 4 in Pipe (Vuik et al., 2010)

Geological Considerations for a Drive Point System

The drive point method is most effective in unconsolidated, sandy formations (A Laymen's Guide to Clean Water, 2015). Drive point drilling is not intended for drilling through hard layers of soil. Koegel states, "Barring impermeable strata the depth to which such a well can be driven depends on the build-up of friction between the well pipe and the material penetrated and the transmission of the force of the driver down the length of pipe" (1985). In loose formations such as sand, the drive point method can be easily managed. Koegel states that using the drive point method, one could drill down about 25-30 m, (80-100ft) (1985). Koegel does not specify a geologic formation nor the driving method (mechanical or hand) that is used in driving down only 25-30 meters. However, Danert points out that in coarse sands, the drive point method can only penetrate about 1-2 meters further by hand once the well has been augered down to near the water table, but can be driven farther if machines are used to assist in the drilling process (2009a). Sometimes driven wells are used in conjunction with another type of drilling method such as hand augering (Koegel, 1985). The Pitcher Pump System currently in use in eastern Madagascar is typically installed this way (MacCarthy, Annis, et al., 2013). Some drillers prefer one drilling method over another; and they drill down to the water table with the preferred method of drilling and then use the drive point method to drill the remaining depth. The drive point method is needed at that point because augering and coring methods are difficult when drilling through water due to the instability of the moist soil, which causes the well walls to cave in.

Drilling in Eastern Madagascar

In eastern Madagascar, Pitcher Pump systems are commonly used for delivering potable drinking water (MacCarthy, Annis, et al., 2013). The well installation process for this system involves the drive point method. This method is typically paired with either coring or augering, and uses a well-point forged out of galvanized iron (GI) piping and attached to a GI well casing. A brass screen is soldered to the GI well casing using lead-tin solder. After augering or coring has been performed down to the water table, the GI pipe is driven in to the ground using a manual hammer. The GI casing is left in the ground and a Pitcher Pump is attached to the top of the pipe. Consequently, the drive casing (or outer well casing) acts as both the riser pipe (pipe that water is pumped through) and the drilling support tool. This can be very costly, since the drillers are using GI pipes (MacCarthy, Annis, et al., 2013).

In eastern Madagascar an indirect type of drive point installation was attempted in July 2013 by University of South Florida researchers. Using this method, a well technician drilled a well using galvanized iron (GI) piping with a detachable well-point. This detachable well-point was stick-welded in four places to the GI drive casing and then hammered down to about 6 m. The first 4 m of well depth were hand-augered. Once at the desired depth, PVC pipe was inserted into the GI pipe, and the GI pipe was detached from the metal well-point and removed from the ground.

During this process, two issues arose. The first was that the bottom of the GI drive casing had slots cut into it. This was a miscommunication from the team and was not supposed to have happened. As a result of the slits in the GI drive casing, sand entered the drive casing and prevented the PVC from attaching to the detachable well-point. Second, the detachable hammering end of the GI drive casing was distorted during hammering, which made it difficult for the PVC pipe to fit inside the GI pipe. Also the polyester well screen (wrapped around the slots on the PVC pipe) was ripped due to the PVC pipe being forced down into the distorted, detachable end of the GI pipe. The drilling technician recommended that the next drilling operation should be tried with the PVC piping already screwed into the detachable well-point. In that case, the drive casing would have to be significantly longer than the PVC pipe in order to prevent it from being damaged during the drive process (MacCarthy, Wahlstrom, Akers, Annis, & Mihelcic, 2013). These ideas were used as a basis for subsequent designs in this study.

Drive Point Standards in Developed Nations

In developed countries, the drive point method has several names including drive point technology (DPT), well-point drilling, direct drive, direct push, and push technology. DPT is the most common term for this drilling method. DPT has grown in popularity over the past 10 years due to its adaptability, low cost, and maneuverability in hard-to-drill areas (Environmental Protection Agency, 2013).

In the United States, driven wells typically have small well diameters (1.25 in. to 2 in. diameter). Pipes of about 3 ft long with male and female threads are used (Environmental Protection Agency, 1997), and the well casing should be either steel or steel-galvanized and must meet local and state well code specifications for dimension and weight. Any standard metal may be used for the well-point screens, but plastic screens may not be used during the driving process (Wisconsin Department of Natural Resources, 2010). The pipes can be pushed, hammered, and/or vibrated into the ground using a wide variety of equipment ranging from manual hammers, to small portable rigs and even heavy trucks (Environmental Protection Agency, 1997).

The drive point method has many advantages in developed countries. It is an economical drilling method, minimally intrusive to the natural formation in the ground, and calls for fewer people to operate the rigs than conventional drilling. Also the drive point method requires smaller equipment than conventional drilling so that it is easier to use in a variety of locations, and it is a very quick drilling method. However, the DPT method is limited in the depth to which it can be drilled (Morley, 1995), and cannot be used to drill through consolidated rock formations (American Society for Testing and Materials, n.d.). DPT drilling is primarily used in areas with sandy soils (Wisconsin Department of Natural Resources, 2010). There can also be difficulty grouting/sandpacking the wells if a protective drive casing is not used during drilling (American Society for Testing and Materials, n.d.).

Well-points are used in both commercial and residential settings. In the United States this includes groundwater monitoring, soil sampling, and in situ measurements. Different methods are used for each type of sampling. Sampling methods include but are not limited to barrel (non-sealed) sampling, piston (sealed) sampling, and cone penetrometer testing (CPT) for *in situ* measurements (Environmental Protection Agency, 1997). In residential areas drive point wells can have potable and non-potable water uses. In Wisconsin drive point wells are typically used for private residential wells serving six or fewer homes, non-community water supplies such as restaurants and gas stations, and non-potable wells (wells not used for drinking or hygienic purposes) (Wisconsin Department of Natural Resources, 2010).

Two types of rod systems can be used during drilling: single-rod (exposed-screen) and cased (protected-screen). The single rod systems are the most common type of system and only use one sequence of rods to drill (Environmental Protection Agency, 1997). In this system the well casing and screen are driven to a specific depth using a single string of rods. The screen is exposed to the soil during the drilling process, so proper well development is important. The EPA discusses one type of single rod system where the PVC well casing and screen are placed around a drive rod that is connected to a metal drive tip. The casing and the screen sit on top of the drive tip and are driven to a specific depth using the drive rod in order to keep from placing stress on the screen. The drive tip is slightly larger than the diameter of the screen so that is reduces friction between the formation and the well screen and casing (Environmental Protection Agency, 2005).

When the cased systems (or the protected-screen wells) are installed, the well screen and piping are either advanced with the drive casing or inserted into the drive casing after the target depth has been reached. The most common protected screen method is when an outer drive casing attached to an expendable drive tip is driven to a specific depth. Next, the well casing and screen are assembled, placing them inside the drive casing, and fastened to the drive tip. The drive casing protects the well casing and screen from becoming clogged and potentially causing cross contamination in different levels of the soil (Environmental Protection Agency, 2005). Both the Exposed-Screen and protected screen systems were used as a basis for alternative drilling systems developed in this study.

Lead in Developing Nations

Lead is a naturally occurring element found in small amounts in the earth's crust. It is soft, dense, malleable and ductile, resistant to corrosion, and its ease of use makes lead common in industrial applications (Live Science Staff, 2013). While lead has beneficial uses, it can also be toxic to humans and animals.

In developing countries, exposure to sources of lead is much more prevalent than in the United States and other developed countries, where many regulations and changes in manufacturing have been legislated. Potential sources of lead poisoning in developing countries are listed in *Table 1*.

Table 1. Developing World—Risk Factors for Lead Toxicity (Falk, 2003)

Exposure
- Multiple sources: differ from those in the United States
- Industrial sites located in or near residential areas
- Hot climates; more intense exposure to outdoor environments
- Child labor
- Inadequate environmental monitoring capacity and data
- Inadequate tracking of lead use and consumption

Health
- Poor nutrition enhances lead toxicity
- Limited knowledge of toxic chemicals among caregivers
- Laboratory monitoring capacity inadequate; lack of equipment and training
- Absence or incomplete disease surveillance
- Drug treatment (chelating agents) often unavailable

Prevention
- Lack of protective or safety equipment or technology
- Poor industrial engineering controls
- Limited safety and hygiene programs
- Absent or inappropriate regulations
- Uneven implementation of standards and regulations
- Rare or infrequent inspections or enforcement
- Slow or incomplete adoption of new measures

Additionally, health care systems in developing countries have limited ability to treat toxic chemical exposures, such as lead poisoning, and chelating agents for treating severe lead poisoning are often difficult to find. As in the United States, numerous focal sources and regional practices can lead to widespread and severe childhood lead poisoning in specific populations (Falk, 2003). *Table 2* below shows major sources of childhood lead poisoning:

Table 2. Childhood Lead Poisoning—Major Sources (Falk, 2003)

United States
- Lead paint

Worldwide
- Lead gasoline
- Lead-glazed ceramics
- Mining and smelting
- Battery repair and recycling
- Cottage industries
- Flour mills
- Medication and cosmetics
- Consumer products
- Other

In general, children are much more sensitive to lead exposure than adults. One study showed that children can absorb up to 50 percent of the lead they ingest and excrete only 32 percent within a couple of weeks. In contrast after a couple of weeks, adults excrete nearly 99% of the lead they ingest (Abadin et al., 2007).

The Pitcher Pump system wells currently being installed in eastern Madagascar use lead-containing materials in the well screen and in the solder used to hold the screen in place. Lead-containing materials were also found in portions of the widely-used Pitcher Pump. While a way has now been found to replace the lead-containing parts in the Pitcher Pump, the need for a viable alternative to brass well screens soldered in place with lead/tin solder is clear, and is the focus of this study.

CHAPTER 3. METHODOLOGY

Alternative Drilling System Design Options

Several alternative design options were considered for the testing phase of this study. Each design utilized non-lead-containing materials and was cost-effective (i.e., not adding significantly to the cost of the current system used in coastal areas of Madagascar). At the outset, two designs were considered, as follows: the Cased System, and the Exposed-Screen System A.

Cased System

For the Cased System, a 25.4 mm (1 in.) diameter PVC pipe was attached to a 25.4 mm (1 in.) diameter drive coupling and well-point by way of a male PVC adapter. The drive coupling and well-point were welded together. An outer drive casing pipe fit around both the drive coupling and the PVC pipe and rested on the outer edges of the well-point. Slots were cut into the PVC pipe 30 cm above the male PVC adapter. *Figure 5* shows a diagram of the Cased System.

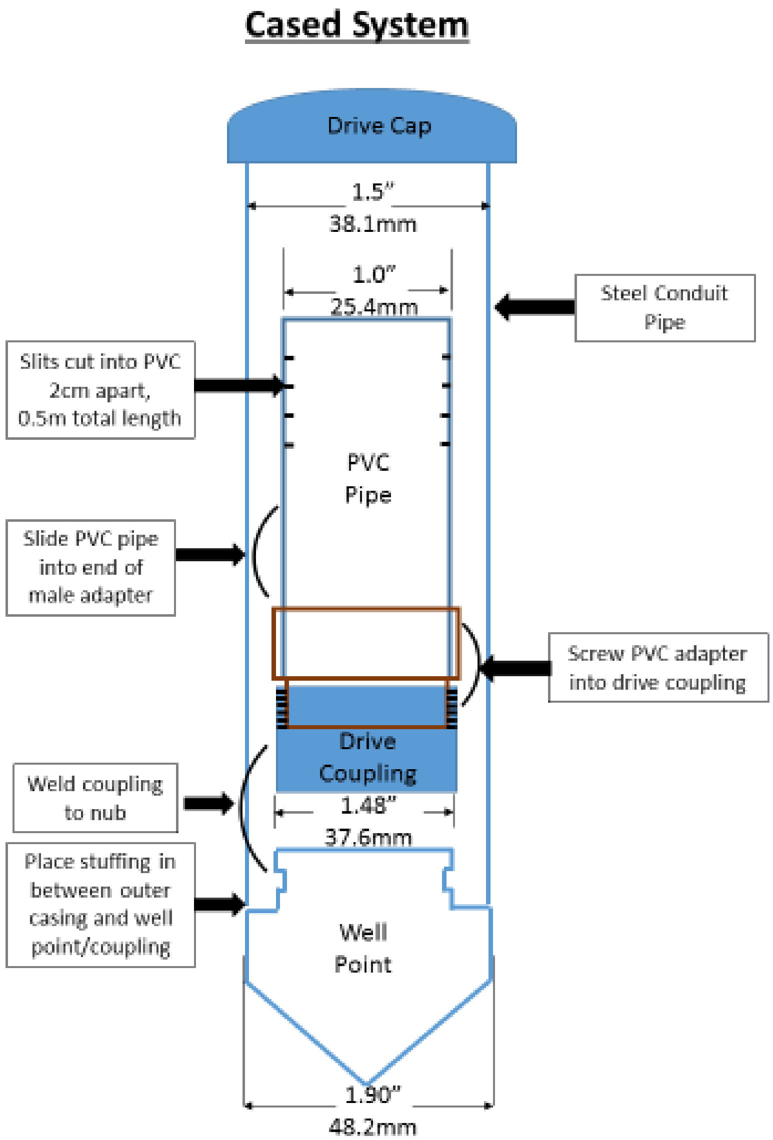

Figure 5. Diagram of the Cased System

Exposed-Screen System A

In Exposed-Screen System A, a 31.75 mm (1.25 in.) diameter PVC pipe was attached to a 31.75 mm (1.25 in.) diameter drive coupling and well-point by way of a male PVC adapter. The drive coupling and well-point were welded together. A 19 mm

(0.75 in.) diameter steel rod was placed inside the PVC pipe to drive the well-point into the ground. Slots were cut into the PVC pipe 30 cm above the male PVC adapter. *Figure 6* shows a diagram of Exposed-Screen System A.

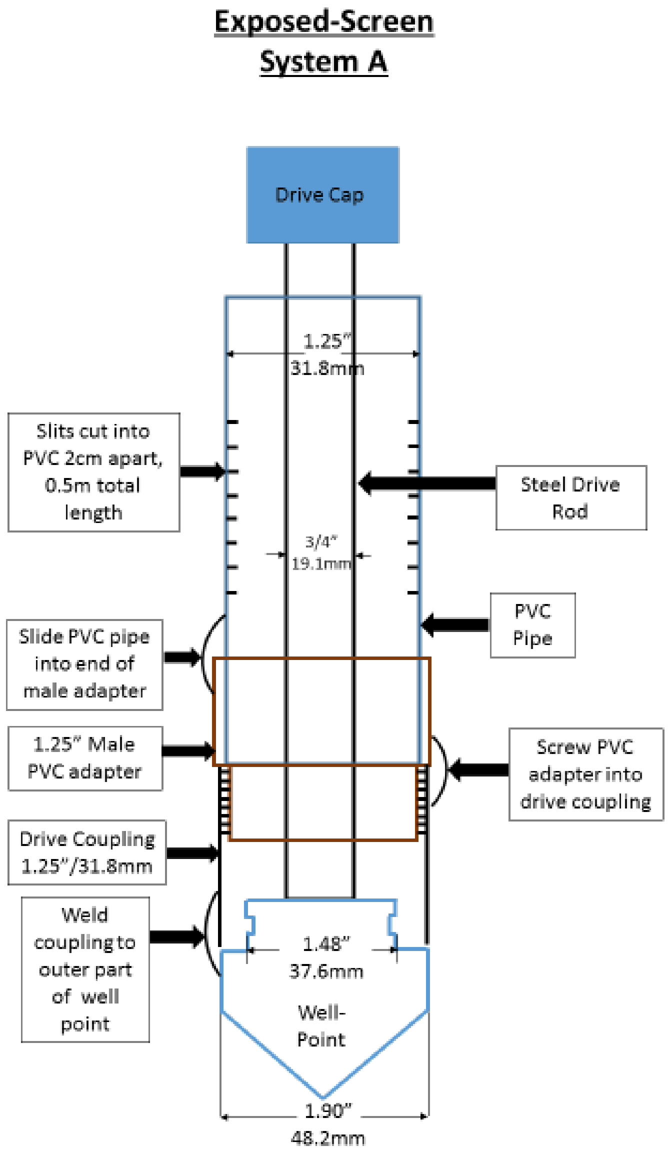

Figure 6. Diagram of Exposed-Screen System A

Parts for these two design alternatives were built and assembled in the machine shop at Mercer University's School of Engineering and transported to Tampa, FL for testing. The Cased System was tested once and Exposed-Screen System A was tested three times in the field.

Exposed-Screen System B

Issues surfaced in both design options during Phase I testing. Of the two design options, Exposed-Screen System A proved to show the most potential. Therefore, after the first set of drilling tests were conducted, modifications to the Exposed-Screen option led to a new, third design option for drilling being developed: Exposed-Screen System B. This third design was tested four times at the field site during Phase II drilling.

In Exposed-Screen System B, 31.75 mm (1.25 in.) diameter PVC pipe (Schedule 40, 370 psi or Schedule 20, 200 psi) was belled out on one end, and a piece of 31.75 mm (1.25 in.) Schedule 20 (160 psi) PVC pipe, the same size as the belled-end, was fitted inside the belled end. The nub of the well-point fit inside the Schedule 20 (160 psi) PVC pipe and was secured by pan head screws. The screws were drilled through the PVC pipe into the nub of the well-point. A 19 mm (0.25 in.) diameter rigid conduit steel pipe was placed inside the PVC pipe to help drive the pipe into the ground. Slots were cut into the PVC pipe 30 cm above the belled-end. *Figure 7* shows a diagram of Exposed-Screen System B.

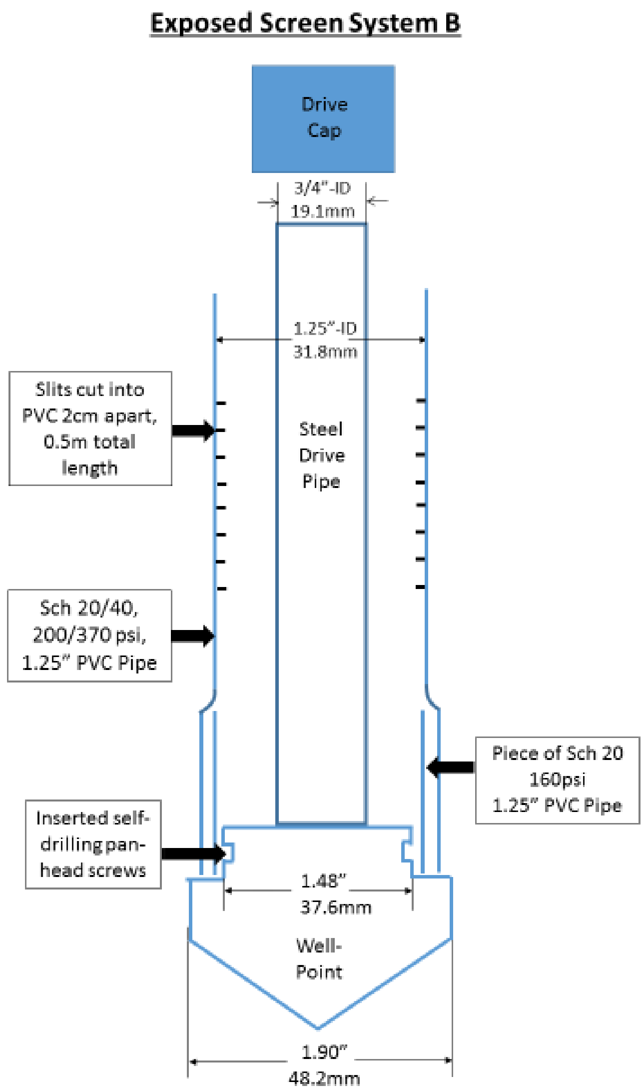

Figure 7. Diagram of Exposed-Screen System B

Additional Considerations for Design Alternatives

Cost

In considering design alternatives, it was important to keep them not only cost-effective but similar to and compatible with the drilling method currently used in eastern

Madagascar. Previous attempts to improve the current methods in eastern Madagascar were also studied and considered (MacCarthy, Annis, et al., 2013), but always with cost in mind. The cost of all materials and tools constructed for this study was approximately US$535. A breakdown of cost estimates for materials can be found in *Appendix A.* The breakdown for the cost of each well is discussed in the results and discussion chapter (Chapter 4).

Diameter of the Drive Pipe

The diameter of the drive pipe was another major concern in choosing design alternatives. Previous drilling attempts by University of South Florida researchers in eastern Madagascar were unsuccessful when the pipe diameter was greater than 50.8 mm (2 in.), because increased friction between the large diameter well pipe (60 mm (2.36 in.) diameter, in that case) and the soil formation led to the drive casing being too difficult to remove from the ground (MacCarthy, Wahlstrom, et al., 2013). For purposes of this study, each design option made for testing utilized a maximum pipe diameter of less than 50.8 mm (2 in.): about 48.3 mm (1.9 in.) for the outer drive casing of the Cased System, and 42.3 mm (1.66 in.) for Exposed-Screen System A and Exposed-Screen System B. Smaller pipe diameters were also considered; however, these smaller pipe diameters would not allow for sufficient water to be pumped from the well.

Building the Cased System

The Cased System was designed so that the outer drive casing pipe protected the inner PVC riser pipe. Without the outer drive casing, the PVC riser pipe could have been exposed to various levels of contamination as the riser pipe was hammered into the ground. The outer drive casing would also prevent the possibility of clogging of the slots that were cut into the inner PVC riser pipe (Environmental Protection Agency, 2005). The slots in the PVC riser pipe allowed water to flow into the pipe (once the outer drive casing was removed) so that water could be pumped out.

Three Cased System prototypes were constructed. The purchased, manufactured well-points were initially over 2.5 in. in diameter and were tapered to about 1.9 in. so that they were flush with the outer diameter of the drive casing for drilling. If the diameter of the drive casing is larger than the diameter of the well-point, major friction issues can arise during drilling. Specifically, as the drive casing is driven down, the outer edges of the drive casing (above the well-point) could catch the inner walls of the well and drastically slow the drilling process.

A 1 in. diameter drive coupling was welded to the nub of the well-point. The inner pipe was 1 in. diameter Schedule 20 PVC pipe at 200 psi. Slots were cut over a half meter length (25 slots) of the 1 in. diameter PVC pipe, at 2 cm intervals. A breathable screen filter sleeve made of 100% polyester fabric was fitted over the slotted area and taped to the PVC pipe. A polyester sleeve was chosen because it is readily available in Madagascar. Also polyester will not decompose in the ground (Buchner, 2010). The 1 in. diameter PVC was connected to a 1 in. diameter male PVC adapter. PVC cement was used to secure and strengthen the bond between the PVC pipe and the PVC adapter. The adapter was screwed into the 1 in. diameter drive coupling once the drive casing was hammered to the desired depth. The outer drive casing was made of 1.5 in. diameter rigid steel conduit pipe and fit over the PVC pipe, drive coupling, and nub of the well-point. In order to secure the drive casing to these inner parts, paper was wrapped around the well-point to fill the gaps between the inside diameter of the drive casing and the well-point nub/coupling. The purpose of wrapping the paper inside the well-point was to make sure it would not fall out of the drive casing as it was being set into the hole. This process can be seen in *Figure 8*. (See also diagram of the Cased System *Figure 5*, page 20).

Figure 8. Paper-Wrapped Well-Point

Building Exposed-Screen System A

Exposed-Screen System A was designed for simpler drilling, installation and cost-effectiveness when compared to the Cased System. With Exposed-Screen System A there were fewer materials and no outer drive casing. The 31.75 mm (1.25 in.) PVC pipe that would be driven into the ground was exposed and had only a screen filter sleeve around the slots that were cut to help filter out large sand particles. The well-point diameter was slightly larger than the diameter of the PVC. This allowed for space between the PVC pipe screen (including the screen filter sleeve) and the walls of the well hole.

Three Exposed-Screen prototypes were constructed. As with the Cased System, the well-point was tapered (in this case to 48.2 mm (1.9 in.)). A 31.75 mm (1.25 in.) diameter drive coupling was welded to the outer edges of the well-point so that the drive coupling and the outer edges of the well-point were flush. The riser pipe was a 31.75 mm (1.25 in.) diameter Schedule 20 (200 psi) PVC pipe. The 31.75 mm (1.25 in.) diameter PVC was connected to a 31.75 mm (1.25 in.) diameter male PVC adapter. PVC cement was used to bond the PVC pipe to the PVC adapter. The PVC adapter was screwed into the 31.75 mm (1.25 in.) diameter drive coupling. During well installation, a 0.75 in. diameter steel rod was placed inside the 31.75 mm (1.25 in.) diameter PVC pipe and used to hammer Exposed-Screen System A into the ground. (See *Figure 6*, page 21 for a complete diagram of Exposed-Screen System A).

Building Exposed-Screen System B

Drilling of the fifth well (Well #5) in Tampa revealed a weak connection in Exposed-Screen System A between the well-point and the PVC pipe, specifically at the male PVC adapter that connects the drive coupling to the well-point. With this issue in mind, a third design option was developed. Exposed-Screen System B was designed to give greater strength to the pipe just above the well-point. The well-point fit directly into the belled-end of a 1.25 in. diameter, Schedule 20 (200 psi) or Schedule 40 (370 psi) PVC pipe. Similar to Exposed-Screen System A, there was no outer drive casing, and the

31.75 mm (1.25 in.) diameter PVC pipe that was being driven into the ground was exposed and had only a polyester screen sleeve around the slots to help filter out large sand particles. The belled-end of the PVC pipe was made by heating the end of a pipe and fitting another piece inside the heated piece. *Figure 9, Figure 10, and Figure 11* show the process of belling out a PVC pipe.

Figure 9. Heating a PVC Pipe

Figure 10. Belling Out a PVC Pipe

Figure 11. Final Result of Belling-Out a PVC Pipe

Once the belled-end was made, a separate piece of 1.25 in. diameter Schedule 20 (200 psi) PVC pipe was fitted into the belled-end. This reinforced the belled-end of the PVC pipe during the hammering process. In addition, four self-drilling screws were installed around the belled-end PVC pipe to hold the well-point in place during the drilling process. A 0.75 in. diameter steel pipe was placed inside the 31.75 mm (1.25 in.) diameter PVC pipe and used to hammer Exposed-Screen System B into the ground. (*Figure 7*, page 23, shows a complete diagram of Exposed-Screen System B).

Two Exposed-Screen System B's were made with Schedule 40 (370 psi) pipe and two were made with the Schedule 20 (200 psi) PVC pipe. The purpose of using two different strengths of pipe was to first make sure that the belled-end neck area of a Schedule 40 PVC pipe was strong enough to withstand hammering; and if that was successful, then a Schedule 20 (200 psi) pipe would be tested, the latter being more readily available in Madagascar. Both sets of pipes had Schedule 20 (200 psi) PVC pipe inside the belled ends to reinforce the bottom end of the pipe closest to the well-point.

Additional Drilling Preparation

Well Screen Development

Two methods were used to cut slots into the PVC pipe. The first method was used for the Cased System and for the first two wells of Exposed-Screen System A. Slots were cut into the PVC pipe, beginning 30 cm up from the male PVC adapter. The 30 cm length was chosen so that there would be a large enough sump for any sand that passed through the screen sleeve into the pipe to settle and not clog the inside of the screen. The Practica Foundation suggests using 1 m of sump for a 4 in. diameter screen (Vuik et al., 2010); however, for the purpose of this study, drilling was not deeper than 3.5 m, and the screen pipe diameter did not exceed 1.9 in.. Therefore, the length of the sump needed to be smaller, and much of the 1 m was used for screen space.

Using a hacksaw, a total of a half meter of slots was cut into the pipe. Before sawing, six parallel lines were drawn along the half meter of pipe. For the 1 in. diameter riser pipe in the Cased System, the spaces between the alternate lines were drawn at approximately 1 cm and 2.5 cm intervals. The slots were sawed between the 2.5 cm lines. The distance between the slots was approximately 1 cm. *Figure 12* shows how the slots were cut around the pipe using the first method, and *Figure 13* is a picture of the first method of screen cutting.

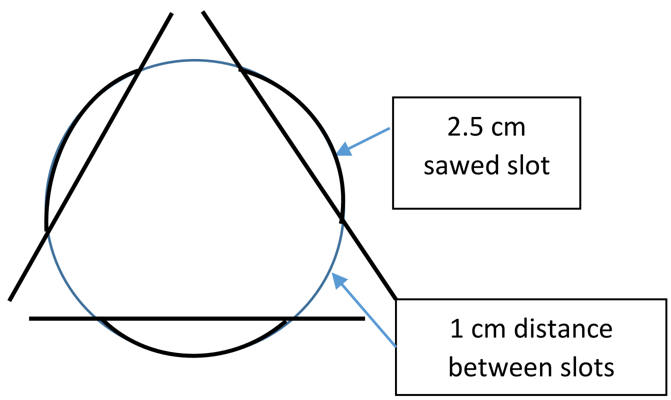

Figure 12. Diagram of Slot Cutting

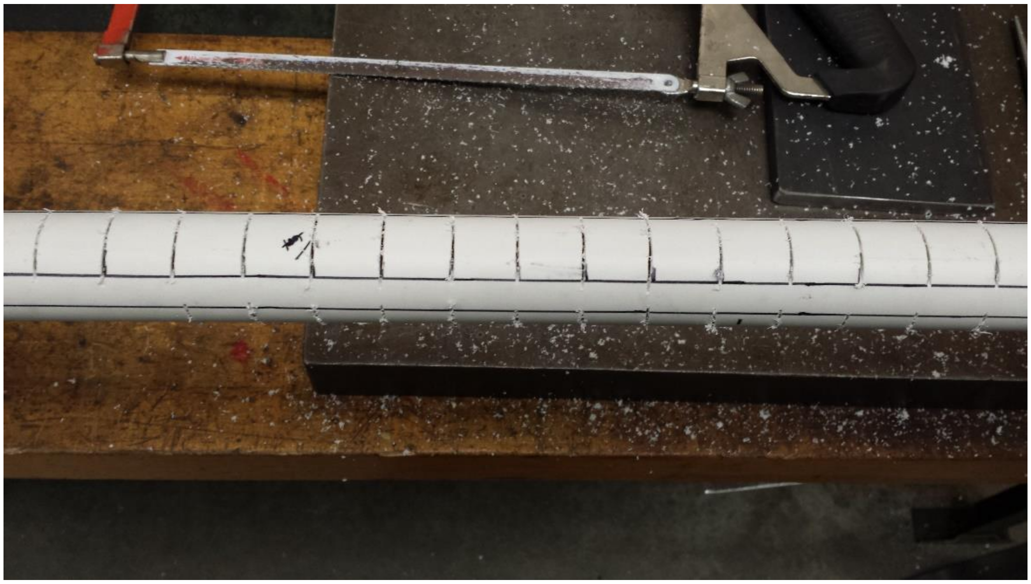

Figure 13. First Method of Screen Cutting

For the 1.25 in. diameter PVC pipe in Exposed-Screen System A, the method was the same except that the spaces between the alternating lines were about 1.5 cm and 3 cm respectively. The slots were sawed between the 3 cm lines, so that the distance between the slots was about 1.5 cm. Each level of slots was spaced 2 cm apart along the half meter-long section of pipe.

Revised Method for Cutting Slots. A second method for cutting slots was implemented in the field after the slotted portion of the PVC pipe used in Well #3 broke off at the first layer of slots. The first method had not allowed for adequate strength and stability in the PVC pipe between the slots, so an alternate method was devised for the last two wells that were to use Exposed-Screen System A, and for all of the belled-end wells. This method consisted of slots along a half meter of pipe beginning 30 cm up from the male adapter/belled-end. Slots were cut every two centimeters at about a 30 degree angle, rotating the pipe 180 degrees every ten centimeters of cuts. This strengthened the pipe and distributed pressure on opposite sides of the pipe. A total of 25 cuts were made. *Figure 14* shows how the second series of slots were cut.

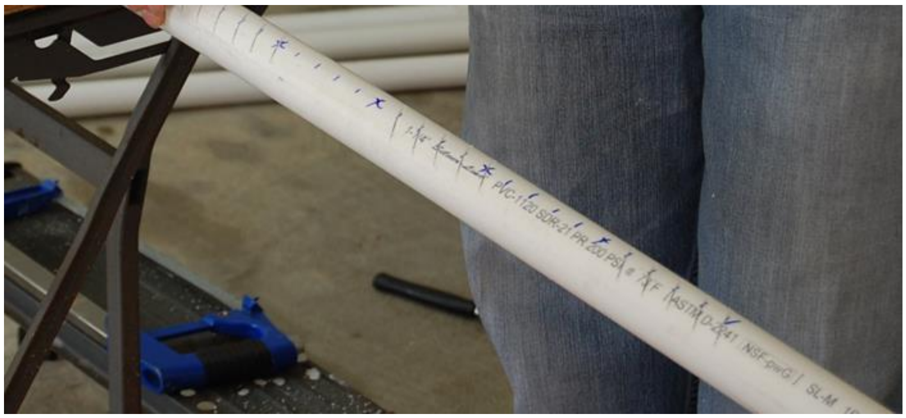

Figure 14. Second Series of Cuts

Modification of the Drive Hammer

An HDX brand fence post driver (Model# 901147HD) was purchased and used for driving the pipes into the ground. This was selected as the hammer of choice due to 1) its cost, 2) its ergonomic design, and 3) the possibility that a similarly built tool could be utilized in Madagascar.

The fence post driver had two handle bars, one on either side of the driver, that were angled at about 45 degrees to help with the ergonomics of the hammer. The drive hammer weighed approximately 16 lbs when first purchased. Additional weight was added to enable the fence post driver to hammer the pipe down farther with each stroke, easing stress off the user from pounding. Two three-pound square steel rods were welded on opposite sides of the fence post driver to counterbalance the weight. The total weight of the fence post driver, with the additional steel rods welded to the driver was 9.5 kg, or approximately 20 lbs. *Figure 15* shows the modified drive hammer.

Figure 15. Modified Drive Hammer

Construction of the Drive Cap

Three aluminum drive caps were designed to protect the threads of the pipes that were being driven into the ground and provide added stability for the drive hammer during the driving process. Aluminum was used because it is a softer, more malleable metal than steel with tensile strength sufficient to prevent the threads from being damaged by the forces of the drive hammer. Two of the drive caps were 2.25 in. in length and about 60.2 mm (2.37 in.) in diameter. A 49 mm (1.93 in.) diameter hole was bored in the center of each drive cap, and each hole was bored to a depth of about 29.3 mm (1.15 in.) into the drive cap.

Modified Drive Cap. A third drive cap was made for the second trip to Tampa. It was also aluminum and was about 60.2 mm (2.37 in.) in diameter. This drive cap was made specifically to fit over the 0.75in. drive pipe. For greater stability, the drive cap was made a little longer, 72 mm (2.83 in.). The center of the drive cap was bored deeper, 46.4 mm (1.83 in.), and the diameter of the boring was smaller, 29.5 mm (1.16 in.).

Experimental Drilling

The Drilling Site

Drilling experiments took place in the GeoPark on the campus of the University of South Florida in Tampa, Florida between December 13 and December 15, 2014 and between January 4 and January 6, 2015. This location was selected because of the similarity of its soil make-up to that of the eastern coast of Madagascar. Specifically, a large sinkhole at the USF GeoPark has been naturally filled in with sand over time (Resto et al., 2013), providing a test area for shallow borehole drilling that is very similar to sandy areas in eastern Madagascar (MacCarthy, Annis, et al., 2013).

A soil survey taken by researchers with the Natural Resources Conservation Service (NRCS) found that the soil at the GeoPark at USF is made up of a majority of fine sands (Natural Resources Conservation Service, n.d.). See *Appendix B* for Soil Survey. In order to get replicable results, drilling needed to be performed in an area in which the soil was made up of majority sand and as little clay as possible.

Soil Sampling

Three to four soil samples were taken for each well in order to ascertain the soil make-up at each well site. In general, the soil color for each well became lighter as the well was drilled deeper. Many of the samples contained organics in the first meter of soil, and patches of clay were discovered in certain wells at depths of approximately 2 m and deeper. Soil samples were classified based on the soil classification system found in *A Field Guide to Environmental Engineering* (Mihelcic et al., 2009).

Coring

A total of nine wells were drilled. The drilling process began with selection of a suitable area and coring down to a certain depth before installing the system. *Figure 16* shows the relative locations of each well in the GeoPark.

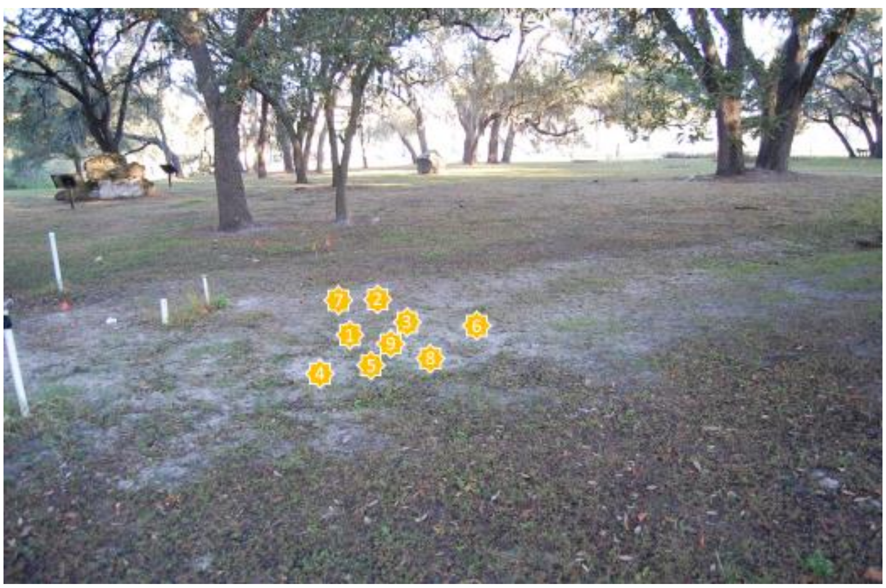

Figure 16. Relative Location of Each Well in the Geopark

At the beginning of the drilling process, either coring or augering could have been used, as both methods are commonly used in eastern Madagascar. Coring was selected for this study due to the tools available at the time of drilling. Coring consisted of using a Schedule 40 (370 psi) PVC pipe and pushing it into the ground while rotating the pipe. Once the pipe was pushed a certain depth into the ground, it was retracted from the ground while holding a hand over the top piece of the pipe so that air could not enter or escape, creating a suction that would hold the soil inside the pipe until the pipe was out of the ground. The pipe was then put back in the ground, and the procedure was repeated until the desired depth was drilled. *Figure 17* shows an example of coring.

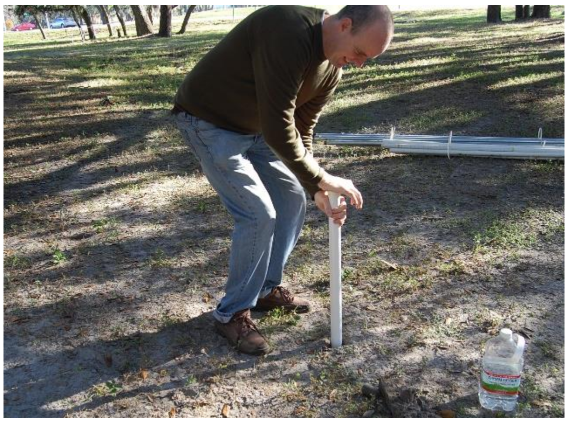

Figure 17. Example of Coring

Phase I Drilling

During Phase I experiments (December 13 – 15, 2014), two methods were tested and five wells were drilled at the USF GeoPark. Each well was first cored using a 38.1 mm (1.5 in.) diameter PVC pipe until it was no longer possible to core, and then drilled using one of the two experimental methods for the remainder of the distance. The first well was drilled in a way that is typical of how wells are drilled in Madagascar, where drillers auger or core down until the water table is reached or until they cannot core or auger any more. Then well-point drilling is used until the desired depth is reached (MacCarthy, Annis, et al., 2013).

Cased System

Well #1. The Cased System drilling method was used for Well #1. Well #1 was first cored to a depth of about 1.5 m (4.92 ft), then the well casing was installed and hammered into the ground an additional 2 m (6.56 ft). Coring of Well #1 can be seen in *Figure 18*.

Figure 18. Coring of Well #1

At about 0.5 m (1.64 ft) the soil appeared to be fine sand with black organics. At 1 m (3.28 ft) the sand became clumpy and turned gray, and at 1.45 m (4.76 ft) the soil was a muddy, light gray sand. At this point the drilling system appeared to reach the top of the water table and could no longer be cored.

Next, preparations were made to install the outer drive casing of the Cased System. The well-point was wrapped with paper to make sure that it would not fall out of the drive casing as it was being set into the hole. At this point only the well-point with the outer drive casing was set into the hole. Installation of the Cased System can be seen in *Figure 19*. The 1 in. diameter riser pipe was installed after the well was drilled to the desired depth.

Figure 19. Installation of Cased System

Buffer pipes were used during the hammering process to help protect and ease the stress on the threads and allow the outer drive casing to sit flat and flush on the well-point. Two buffer pipes, one on each end of the main drive pipe, were connected. The drive cap sat on the top buffer pipe — an 11.5 cm (4.5 in.) length pipe — and the buffer pipe connected to the drive casing by way of a drive coupling. The bottom buffer pipe, a 30.5cm (1ft) length pipe, sat evenly on the well-point and was also connected to the drive casing by way of a drive coupling. *Figure 20* shows both the drive cap and the top buffer pipe.

Figure 20. Drive Casing and Buffer Pipe for Cased System

Hammering with the Cased System commenced at about 1.5 m (4.92 ft). This included the measurement of the drive coupling and the well-point, which was about 11 cm (4.33 in.). At 2.55 m (8.37 ft) hammering was paused to add an extra 1.5 m (5 ft) of drive casing. The connection between the drive coupling and the buffer pipe (the top section of the pipe that was being hammered) and the first 10 ft section pipe were examined. As *Figure 21* shows, the connection between the buffer pipe and the 10 ft section pipe was bent at the drive coupling. The buffer pipe was removed and the 5 ft section was added. Plumbers' tape was wrapped around the male threads of the 5 ft drive casing to add support and stability between the threads. Hammering was restarted and eventually stopped at a depth of 3.5 m (11.15 ft).

Figure 21. Bent Drive Coupling

A total of 2 meters (6.56 ft) of the 3.5 meters was hammered using the Cased System. After hammering was complete, a 25.4 mm (1 in.) diameter PVC riser pipe was prepared so that it could be inserted inside the outer drive casing (which would be withdrawn from the ground) and used to pump water from Well #1. A half meter of slots were cut into the riser pipe, and a breathable polyester fabric sleeve was wrapped over the slots to keep large sand particles from entering into the riser pipe. (Too much silt/sand in the riser pipe could prevent water from being pumped out). Then the sleeve was taped on both ends with electrical tape. *Figure 22* shows the preparation of the riser pipe.

Figure 22. Preparation of the Riser Pipe

Finally, the riser pipe was inserted inside the outer drive casing and screwed into a drive coupling that had been welded to the well-point. Next, the outer drive casing was to be removed so that water could flow into the riser pipe to be pumped out. However, the outer drive casing proved impossible to remove, and testing could not be completed. The total depth of Well #1 was 3 m (11.48 ft). This was the deepest of the nine wells.

Exposed-Screen System A

Well #2. The next four drilled wells utilized Exposed-Screen System A. Well #2 was cored down to about 1.35 m (4.43 ft). At about 0.4 m the soil sample consisted of dark gray, smooth sand with a mixture of organics. The second sample yielded a similar soil make-up at about a depth of 1 m, and the last sample at 1.35 m was very moist, with characteristics similar to the first two samples.

Exposed-Screen System A utilized a Schedule 20, (200 psi) pipe. This type of pipe was used because it is similar to the type of pressurized pipe available in eastern Madagascar, and it is a cheaper type of PVC than Schedule 40 or Schedule 80 PVC. This PVC pipe was prepared by slipping a polyester breathable sleeve over the cuts on the pipe and taping each end of the sleeve with electrical tape. Fishing line was then wrapped around the breathable sleeve in order to keep the sleeve from being torn as the pipe was being hammered down. *Figure 23* shows the completed wellscreen.

Figure 23. Completed Preparation of Wellscreen

Before the well-point was placed in the ground, the end was also belled out so that a longer attachment could be added if it was needed. An example of the belling out process can be seen on page 29.

The drive pipe for Exposed-Screen System A was prepared by adding two pieces of buffer pipe to the drive pipe (one on each end of the main drive pipe) in order to protect the threads during hammering and also to give the end of the pipe a strong, firm end piece to strike the well-point. The top buffer pipe that fit inside the drive cap was 15.2 cm (6 in.) and the bottom buffer pipe was 30 cm (11.8 in.). There was concern that the threads would not be strong enough if placed in direct contact with the well-point during the hammering process. *Figure 24* shows the top buffer pipe and drive cap for Exposed-Screen System A.

Figure 24. Top Buffer Pipe and Drive Cap for Exposed-Screen System A

Plumber's tape was used on all male connections on the drive pipe to help support the threads. The same drive cap was used in the hammering process that was used for Well #1. Because the drive pipe was much smaller than the outer drive casing of Well #1, extra material had to be wrapped around the top buffer pipe so that the drive cap could fit securely on the buffer pipe.

Exposed-Screen System A was placed in the ground and the drive pipe was inserted inside the system. Hammering commenced at 1.1 m (3.6 ft). Some of the well wall had collapsed during preparation of Exposed-Screen System A. Hammering stopped at 2.2 m (7.2 ft), and the drive pipe was removed. Water was pumped out of the pipe successfully, and the depth-to-water was measured at about 1.98 m (6.5 ft).

After the depth-to-water was measured, Exposed-Screen System A was removed. Normally, in Madagascar, this system would be left in the ground. However, for purposes of this study, the system was removed so that the screen and other parts of the system could be examined to see if there was any external damage. This was the last well drilled on December 13, 2014.

Well #3. Well #3 was cored to about 1.35 m (4.4 ft) on December 14, 2014. Three samples were taken during the coring. The first sample was taken at 10 cm and consisted of fine, black sand with organics. The second sample was at 0.5 m and the soil was a damp, light gray sand mixed with some black organics. The third and last sample for Well #3 was a very moist, gray and light gray mixed sand with some organics.

Exposed-Screen System A used to drill Well #2 was also used to drill Well #3. Less preparation time was needed for the drilling because it was to be a repetition of the successful drilling process used in Well #2. Exposed-Screen System A was placed in the hole and drilling commenced at 1 m. Again, there was some wall cave-in during the transition from coring to drilling. At 1.3 m hammering was stopped because the pipe broke off at the last 70 cm of the pipe. Modifications to the screen on Exposed-Screen System A were made to the next well that was drilled.

Well #4. Well #4 was cored to about 1.1 m with samples taken at 0.3 m, 0.8 m, and 1.1 m, respectively. The first sample was sandy soil with black organics and some small clay pieces. The second sample was moist sand that was light in color, and the third sample was a fine, dark brown sand.

After coring, modifications were made to the Exposed-Screen System A Method. This time, the second method for cutting slots was implemented on the Schedule 20 (200 psi) PVC pipe. The slots were a half meter in length. A breathable polyester sleeve was used to cover the slots as in the last three wells; however, the sleeve was not taped directly below the male adapter as it had been on the first drilling attempt with Exposed-Screen System A. *Figure 25* shows a picture of the modified system.

Figure 25. Modified System for Well #4 with New Slot Cutting Method

Once the pipe was placed in the ground, some of the PVC pipe had to be cut so that there was enough distance between the drive hammer and the PVC pipe. This was done so that the hammer did not damage the PVC pipe during the hammering process. Hammering commenced at 1 m (3.3 ft). The pipe was hammered to a total depth of 2.5 m (8.2 ft). Once the drive pipe was removed, depth-to-water measurements were taken. The last reading taken was 1.26 m (4.15 ft). After all measurements were taken, the pipe was removed from the ground and examined. The sleeve was noticeably pushed up. Due to this occurrence, notches were suggested for the next Exposed-Screen System A to help the fishing line hold the sleeve in place.

Well #5. Well #5 was cored down to 1.25 m. Three soil samples were taken. The first sample was taken at 0.5 m and was a fine, light brown sand with a small amount of organics. The second sample was taken at 0.8 m and had similar soil characteristics. The third sample was taken at 1.2 m and the soil was a very moist, light brown sand with some organics. After sampling, preparations were made for drilling.

As with Well #4, the slots were cut using the alternative method, having alternating rows of cuts and rotating the pipe 180 degrees every 10 cm of cuts. A few changes were also made in preparing Exposed-Screen System A for drilling Well #5. A Schedule 40 (370 psi) pipe was selected for drilling this well. The schedule 40 PVC pipe has a higher pressure rating than a schedule 20 PVC pipe and has a thicker pipe wall. This stronger pipe was used to see how the drilling/hammering affected different pipes throughout the process.

The pipe was notched out, both above and below the slots, so that the fishing line would have a more secure grip while holding down the breathable sleeve. As with the other wells, the sleeve was slid over the slots in the pipe, and electrical tape was used to secure the sleeve. This time the bottom portion of the sleeve was taped immediately above the male adapter, instead of below the slotted screen. This would help prevent the sleeve from being pushed up. Fishing line was wrapped around the sleeve and secured in both the top and bottom notches. The ends of the fishing line were also taped both above and below the slots to help the fishing line stay in place and to keep it from getting caught up during the drilling process. *Figure 26* shows the system complete and ready to drill.

Figure 26. Finished Exposed-Screen System A

Hammering commenced at 1.1m and was stopped at 2.35 m. The well-point on the end of the pipe broke off at the threads of the male adapter that screws into the drive coupling and well-point. The remainder of the pipe was pulled up and examined. This was the last well drilled during the first trip to Tampa.

Rejection of the Cased System. Being unable to remove the outer drive casing of the Cased System from the ground, as well as the obvious necessity for heavy drilling equipment and multiple moving parts to make the Cased System work efficiently, there seemed to be few solutions for this method, so focus was placed on design modifications for Exposed-Screen System A.

Redesign of Exposed-Screen System A. To prevent the well-point from breaking off at the coupling connection, a modification to the 1.25 in. diameter PVC pipe was discussed and developed so that the end of the system closest to the well-point would be stronger and more reliable in the drilling process. This new system was called Exposed-Screen System B. To help with the stability of the hammering process, a new drive cap was created to fit the diameter of the 0.75 in. diameter drive pipe. Like the first two drive caps, this drive cap was made out of aluminum but was bored deeper and with a smaller diameter for greater stability during the hammering process. *Figure 27* shows the new drive cap.

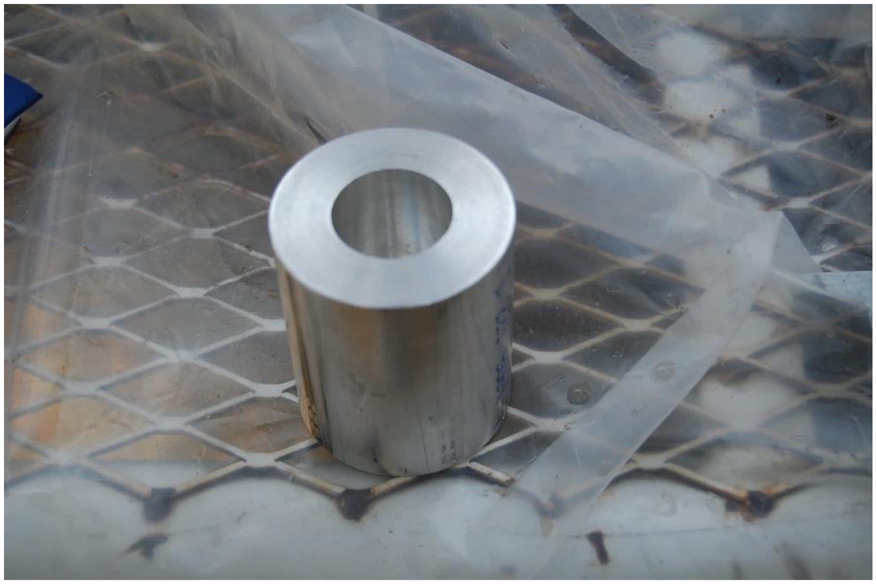

Figure 27. New Drive Cap for 0.75 in. Drive Pipe

Phase II Drilling

Exposed-Screen System B

Exposed-Screen System B was tested in a second trip to the University of South Florida's GeoPark in Tampa, Florida. For the second set of experiments (January 3-5, 2015) four wells were drilled using the Exposed-Screen System B Method. Once again, each well was first cored out using a 38.1 mm (1.5 in.) diameter PVC pipe until it was no longer possible to core, and then drilled using the Exposed-Screen System B Method for the remainder of the distance. Soil samples were also taken about every half meter for each well.

Well #6. Well #6 was cored to a depth of 1.25 m (4.10 ft). Three soil samples were taken at 0.5 m, 1 m, and 1.25 m, respectively. The first soil sample was a fine, light brown, smooth sand. Both the second and third soil samples shared similar characteristics as the first sample. Coring stopped at 1.25 m (4.10 ft) and preparations were made for the first Exposed-Screen System B.

The first system utilized a Schedule 40 (370 psi) pipe. Since the Schedule 40 pipe is a stronger pipe, it was chosen to be used first. If that drilling was successful, then a Schedule 20 (200 psi) PVC pipe would be used. Similar to the preparation process for Exposed-Screen System A during Wells #4 and #5, slots were cut on Exposed-Screen System B using the method developed in the field. It was important to keep the same type of preparation process as before so that it would be easier to narrow down the problems if there were any. A polyester sleeve was then fitted over the slots. The sleeve was made for a 1.25 in. diameter pipe instead of a 1.5 in. diameter PVC pipe. The sleeve was sized correctly and fit comfortably over the PVC pipe but was not taped directly below the belled-end side of the pipe. The pipe was also notched out above and below the cuttings on the pipe, and fishing line was wrapped around the notches and the sleeve. Then electrical tape was used to secure the fishing line in the notches on both sides of the slot cuttings. *Figure 28* shows the preparation of Exposed-Screen System B for Well #6.

Figure 28. Preparation of Exposed-Screen System B

Exposed-Screen System B was inserted into the ground and hammering commenced at about 1.2m (3.9 ft). Hammering was stopped at 2.2 m (7.22 ft). There was difficulty removing both the drive pipe and Exposed-Screen System B. Water was poured into the PVC pipe to help loosen sand that might have been inside. Eventually, the inner drive pipe was pulled out of the PVC pipe, and the depth-to-water measurement was taken (after allowing for the water level to stabilize) and measured at 1.43 m (4.7 ft). The PVC pipe was then removed from the ground.

Well #7. Well #7 was cored down to about 1.3 m (4.27 ft). Three soil samples were taken, at 0.5 m, 1 m, and 1.3 m, respectively. The first soil sample was a light brown, fine sand. The second soil sample was a light gray fine sand with some organics, and the third soil sample was a fine, white sand with a few clay pieces. Coring stopped at 1.3 m.

The preparations for Well #7 were primarily the same as those of Well #6, with a few modifications. This time the notches were cut directly under the belled-end and about 15 cm away from the slots on the opposite end. The sleeve was set immediately after the belled-end on the PVC pipe, and fishing line was wrapped around the notches, over the sleeve, and taped on both sides of the cuttings. The pan-head screws on the belled-end of the PVC pipe were also filed down so that they did not protrude and risk getting caught as the pipe was being drilled down.

Hammering of Exposed-Screen System B commenced at 1.3 m (4.92 ft) and was stopped at 2.3 m (7.55 ft). During the hammering process, shorter strokes were taken with the drive hammer in order to help with preventing external damage to the PVC pipes. The drive hammer was raised approximately 15 cm for every stroke. After drilling, the drive pipe was easily removed with no issues, and the depth-to-water reading was 1.55 m (5.08 ft). The PVC pipe was then removed from the ground and analyzed.

Well #8. Well #8 was cored down to about 1.25 m (4.10 ft). Three soil samples were taken, at 0.5 m, 1 m, and 1.25 m, respectively. The first soil sample was a fine, light brown sand. The second soil sample was a fine, light gray sand with some organics, and the third soil sample was similar to the second soil sample but without organics.

After coring, preparations were made similar to those made for the previous two wells, with a few additional modifications. Instead of using 1.25 in diameter, Schedule 40 (370 psi) PVC pipe, a 1.25 in, Schedule 20 (200 psi) PVC pipe was used for the drilling. Since the Schedule 40 PVC pipe was not damaged in the previous two drillings, Schedule 20 PVC pipe was tested using the Exposed-Screen System B Method to see if the strength of the Schedule 20 pipe would hold up as well as the Schedule 40 pipe. PVC cement was added to help secure the breathable sleeve and was applied on both ends of the sleeve and in between the slots on the screen. Like the notches, the breathable sleeve was started immediately after the belled-end and extended down to 15 cm past the cuttings that form the screen. Fishing line was applied after the PVC cement dried and the screws were again filed down on the belled-end. *Figure 29* shows the Schedule 20 PVC pipe for Well #8 prepared and ready.

Figure 29. Schedule 20 PVC Pipe for Well #8 Prepared and Ready

The PVC pipe was inserted into Well #8, and hammering commenced at 1.2 m (3.94 ft). During the hammering process, the drive hammer was lifted only 15 cm for each stroke. Like Well #7 the strokes were made shorter. Hammering stopped at 2.1 m

(6.89 ft) and the drive pipe was removed. A depth-to-water measurement was taken, which was 1.90 m (6.22 ft), and the PVC pipe was removed from the ground.

Well #9. The goal for Well #9 was to replicate the successful process used with Well #8. Well #9 was cored down to about 1.45 m (4.76 ft). Three soil samples were taken, at 0.5 m, 1 m, and 1.45 m, respectively. The first soil sample was a fine, light brown sand with a small amount of organics. The second soil sample was a fine, moist, light brown sand with some organics, and the third soil sample was a moist mixture of fine, light gray and brown sand containing organics. The same preparations were made for the prototype in Well #9 as for Well #8, except that for Well #9, PVC cement was only applied to the ends of the breathable sleeve instead of in between the slots on the screen.

Hammering began at 1.3 m (4.27 ft) in the ground. The same hammering process was used for Well #9 as was used in Well #8. Hammering stopped at 2.32 m (7.61 ft), and the depth-to-water measurement was 1.52 m (5 ft).

Phase III Drilling

Madagascar Exposed-Screen System

The Madagascar Exposed-Screen System (called the "Madagascar System" for the purpose of this study) was designed using what had been learned from the previous drilling experiments, and combining that information with modifications to the system in order to make sure that the system was feasible in eastern Madagascar. *Figure 30* shows the design for the Madagascar Exposed-Screen System.

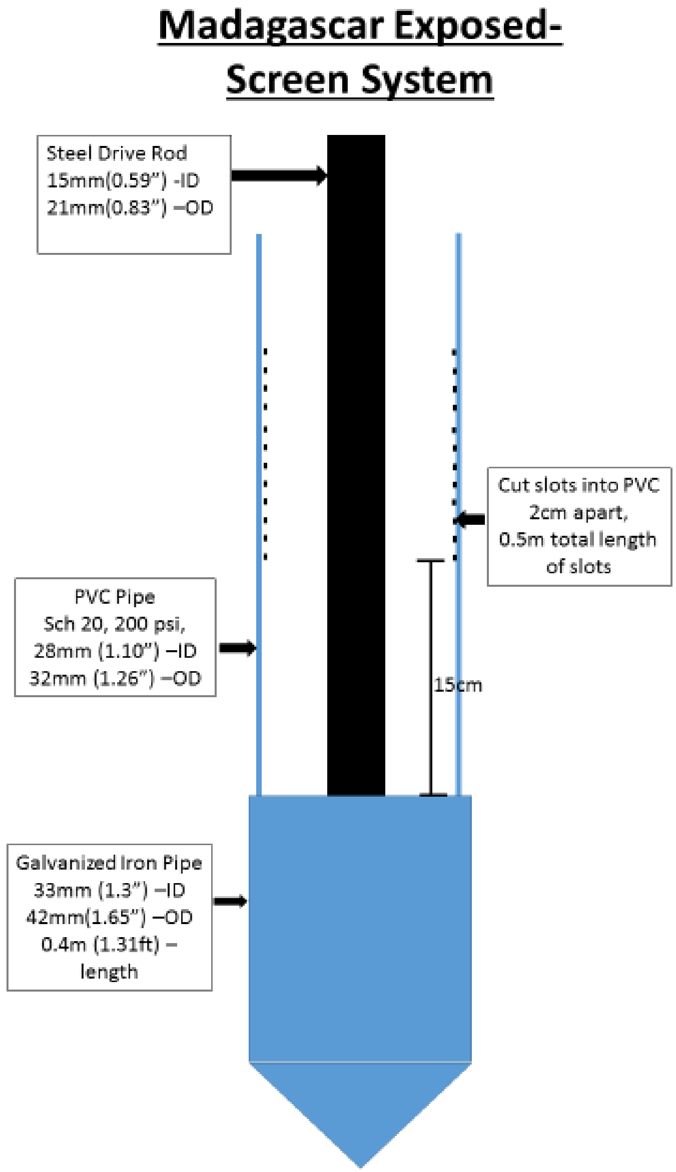

Figure 30. Madagascar Exposed-Screen System

The Madagascar System was similar in design to both Exposed-Screen System A and Exposed-Screen System B. Coring was needed before hammering, and a 15 mm x 21 mm (about 0.59 in. x 0.83 in.) diameter galvanized iron drive pipe was used to drive the system into the ground. Pressurized PVC pipe 28 mm x 32 mm (about 1.1 in. x 1.3 in.)

acted as the outer casing, and the slots were made using the same alternative cutting method as those in Phase I and Phase II. Note that pipes purchased in Madagascar were not the same diameter size as those in the United States due to the differences in the unit systems used in each country. A breathable sleeve was sewn to fit the pipe and both ends were attached to the PVC pipe using PVC cement.

The largest modification was the well-point. The well-points used for drilling in the first two phases of this study were standardized, manufactured well-points. However, in eastern Madagascar, well-points are galvanized iron pipes that are forged into points by local blacksmiths. After the forging process is complete, paper material was wrapped around the lower end of the PVC pipe, and the galvanized well-point was fitted around the outside of the lower end of the PVC pipe.

Drilling in Madagascar

Two wells were drilled in Tamatave, Madagascar on February 4 and February 5, 2015. A research assistant was hired to oversee the work of the drilling technician. A materials list, step-by-step pictorial assembly, installation, and deconstruction guidelines were sent to Madagascar to help the research assistant and driller understand the desired drilling process (see *Appendices C, D, E, and F*). All materials were purchased locally. PVC pipe (6 m in length), GI drive pipe (6 m in length), electrical tape, a breathable sleeve (to cover the screen), PVC cement, and fishing line were purchased. Pricing for the materials can be seen in *Appendix J.* The forging of the well-points was outsourced to a local blacksmith, and the sewing of the polyester filter sleeve to a local seamstress.

Both systems were built and assembled by the driller. *Figure 31* shows a picture of one of the completed systems.

Figure 31. Completed Madagascar System

The same drilling process was used for both wells. The two wells were first cored down to the water table. Next, a GI pipe was inserted and hammered down farther. (Note: this step in the process was not in the drilling instructions sent over to Madagascar.) The GI pipe was retracted, and the Madagascar System was inserted. The driller hammered on the PVC pipe (See *Figure 32*).

Figure 32. Hammering on PVC Pipe

This was not in the drilling instructions and was believed to be a miscommunication. Only about three-quarters of the PVC pipe was hammered because the driller did not use the drive pipe as instructed. After receiving new instructions a few days later, the driller used the drive pipe to help complete the drilling of both wells. Finally, delayed by extreme weather conditions, the driller deconstructed the well and examined it one week later according to the deconstruction instructions that had been sent (See Appendix F).

CHAPTER 4. RESULTS & DISCUSSION

Phase I Drilling

Two trips were made to Tampa, FL to carry out experimental drilling. Each trip was three days long and included both preparation and experimentation. Drilling took place at the University of South Florida's GeoPark (USF GeoPark). The two drilling experiments were divided into Phase I and Phase II. Phase I consisted of the first trip to the USF GeoPark from December 13-December 15, 2015 and included testing both the Cased System and Exposed-Screen System A.

The Cased System

Well #1. The Cased System drilling method was used for Well #1. No difficulties were experienced during the coring phase of the drilling; however, the outer drive casing could not be removed from the ground to allow water into the inner riser pipe, and testing could not be completed. Later, after drilling into clay with Well #9, the reason for the difficulty in Well #1 became clear: a clay layer began at about 2 m (6.56 ft). Therefore, the Cased System could have been in as much as 1.5 m (4.92 ft) of clay. Clay particles can be extremely "small and 'sticky'" (Van der Wal, 2010). As a result, clay can be extremely difficult to drill through using a drive point method. Augering through clay first could help ease the drilling process. Because of the difficulties experienced, only one well was drilled with the Cased System, and the Cased System was abandoned as not practical/feasible for the conditions encountered at the USF GeoPark.

Exposed-Screen System A

Well #2. Wells #2-5 utilized Exposed-Screen System A. Well #2 was drilled and then removed from the ground successfully. Exposed-Screen System A showed no visible damage to the exterior, and the breathable sleeve was still in place, as it had been before the well was drilled. *Figure 33* shows Exposed-Screen System A for Well #2 after drilling.

Figure 33. Exposed-Screen System A after Drilling

Well #3. During the drilling of Well #3, Exposed-Screen System A broke off at the first cut that started the screen, and the lower 70 cm of the PVC pipe was lost. This system was the same one that had been used in Well #2. The break at the beginning of the screen was a clean break. Two causes were thought to have contributed to the breaking of the PVC pipe:

1) lack of strength in the screen area of the PVC pipe (the three sets of slots made in the pipe with 1.5 cm between each set of slots had decreased the pipe's strength and stability); and
2) constant pressure from repeated hammering during Well #2 drilling may have weakened the stability around the screen area of the PVC pipe. To prevent another such breakage, a new set of slots was cut, with the goal of strengthening the PVC pipe so that it could be hammered into the ground. *Figure 34* shows the break in the pipe for Well #3.

Figure 34. Break in Pipe for Well #3

Well #4. Well #4 posed no problems during the coring and hammering phases. However, after removing the pipe from the ground, it was observed that the breathable sleeve was noticeably pushed up. (*Figure 35* shows the sleeve pushed up for Well #4). This likely happened during the hammering process. The sleeve had been made for a 1.5 in. diameter PVC pipe; and the pipes that were being used in drilling were 1.25 in. in diameter. However, when the sleeve was taped to the pipe, the tape may have been too high up on the pipe, which could have allowed dirt or roots to get under the tape during the drilling process. The pipe for Well #2 did not have a pushed up sleeve; however, in that case the sleeve had been taped closer to the male PVC adapter.

Figure 35. Sleeve Pushed Up on Well #4

Well #5. A few changes were made in the preparation for the installation of Exposed-Screen System A for Well #5. A stronger pipe was used (Schedule 40 pipe instead of Schedule 20), notches were made above and below the screen, and the bottom portion of the breathable sleeve was taped directly above the male adapter. Toward the end of the drilling process, the end of the pipe broke off at the threads of the male adapter, and the drive coupling and well-point were lost. Upon retrieval of the system, the sleeve was found to be pushed up over the screen, similar to what had happened in Well #4. Pictures of the remaining drilling system are shown in *Figure 36 and Figure 37.*

Figure 36. Failed Screen on Well #5

Figure 37. Failed PVC Adapter on Well #5

Addressing Problems Encountered in Phase I

Refinements Made to Exposed-Screen System A

The major issues encountered with Exposed-Screen System A were:

- the weak connection between the PVC male adapter and the drive coupling;

- the sleeve being pushed up; and
- the first method for cutting slots to make the screen, which significantly weakened the PVC pipe.

Addressing the matter of weak connection between the PVC male adapter and the drive coupling began with the threads on the male adapter. The threading on the adapter removed about half of the thickness of the threaded portion of the male adapter, making the threaded portion of the PVC adapter the weakest connection between the PVC riser pipe and the well-point. Additionally, the constant hammering on the nub of the well-point may have placed stress on the components to which the well-point was connected, i.e., the male adapter and the stainless steel drive coupling. The combination of the stress from hammering the well-point and the weak connection between the drive coupling and the PVC male adapter may have caused the pipe to break at the threads of the male adapter during the hammering process.

Securing the Sleeve. The breathable polyester sleeve was pushed up in Wells #4 and #5. In order to keep the sleeve from being pushed up, two solutions were tried in the second phase of drilling. First, the notches were made as close to the belled-end of the pipe as possible. Second, the sleeve was taped as close to the end of the pipe as possible. The idea was that the connections on the end of the PVC pipe (including the drive coupling, male adapter, and well-point) are wider than the riser pipe that the sleeve and notches are on, and therefore, thus protecting the sleeve from being pushed up by the well walls as the system is hammered into the ground. These ideas were implemented during the drilling of Well #7. Another solution was to protect the sleeve using PVC cement to seal the ends of the breathable sleeve so that no water or sand/mud could get under the sleeve and push it up. This idea was implemented in the field during the drilling of Wells #8 and #9.

Strengthening the Screen. The issue with strengthening the screen was resolved in the field by implementing an alternate method for slot cutting, which consisted of alternating diagonal cuts 180 degrees every 10 cm for a half meter in order to strengthen the PVC. Alternating the cuts every 10 cm allowed for fewer cuts, which strengthened the PVC pipe and still allowed water to come into the pipe from all sides and be pumped out. This was implemented for the remainder of the drilling phases (Wells #4-9).

Phase II Drilling

Phase II drilling was conducted during a second trip to the University of South Florida's GeoPark in Tampa, Florida. For the second set of experiments (January 3-5, 2015) four wells were drilled using Exposed-Screen System B.

Exposed-Screen System B

Exposed-Screen System B was designed as a modification to Exposed-Screen System A. The goal was to strengthen the area of the PVC pipe closest to the well-point. This was accomplished by inserting a short piece of PVC pipe inside the belled-end of another PVC pipe and then attaching the well-point to the same belled-end. This doubles the strength of the area closest to the well-point.

Wells #6 and #7. Wells #6 and #7 were hammered using Schedule 40 PVC pipe with Schedule 20 on the inside of the belled-end. The same modifications that were used during drilling of Exposed-Screen System A were made on the new Exposed-Screen System B in Well #6. The goal of Well #6 was to test the new drilling system to make sure that the well-point did not break off from the rest of the system. Analysis of the PVC pipe pulled from the ground after drilling Well #6 revealed that the Schedule 40 portion of the belled-end was not broken off but was cracked at the edge, where screws had been placed to hold the well-point in place. Additionally, there was a piece chipped off in approximately the same area. It appeared that the screws may have caught on something as the pipe was being hammered down, which may have put pressure on the screws and caused the screws to bend and crack the PVC. Also, the tape did not hold, and the sleeve was pulled down towards the well-point. Analysis of the interior of the PVC pipe showed mud and soil filled the bottom portion of the PVC pipe. *Figure 38 and Figure 39* show the remains of Exposed-Screen System B for Well #6.

Figure 38. A Broken and Cracked Belled-End

Figure 39. Sleeve Pulled Down on the Belled-End

The drilling of Well #7 mimicked the drilling of Well #6. Slight modifications included notches cut directly under the belled-end and placement of the sleeve immediately after the belled-end. In addition, the pan-head screws on the belled-end of the pipe were filed down, and shorter strokes were made during the hammering process. After the hammering process the system was removed. No visible external damage to the belled-end of the pipe or the screws was found; however, the sleeve was pushed up about 0.25 m. *Figure 40* shows the PVC pipe after drilling Well #7.

Figure 40. PVC Pipe after Drilling Well #7

Wells #8 and #9. Wells #8 and #9 utilized Schedule 20 (200 psi) PVC pipe with Schedule 20 (160 psi) on the inside of the belled-end. Since the Schedule 40 PVC pipe was not damaged in the previous two drillings, Schedule 20 PVC pipe was tested. Several additional changes were made to Well #8 to help prevent the sleeve from sliding up. PVC cement was added to help secure the breathable sleeve. As with the previous well, notches were cut directly under the belled-end, and fishing line was wrapped around the breathable sleeve. Additionally, the length of each stroke was set at 15 cm, to minimize vibration that could disturb the PVC where it is attached to the well-point. After hammering, the PVC pipe was removed from the ground. There appeared to be no external damage to Exposed-Screen System B, and the sleeve remained in the same location as it was before the drilling process began. *Figure 41* shows Exposed-Screen System B after drilling Well #8.

Figure 41. Exposed-Screen System B after Drilling Well #8

The goal for Well #9 was to replicate, successfully, the result achieved in Well #8. The same preparations were made and the 15 cm stroke length was used during the hammering process. There was some difficulty removing the PVC pipe from the ground. Once removed, there was a noticeable amount of clay around the well-point area of the PVC pipe, which may have caused the difficulty in removal. The sleeve remained in place and had not moved during the hammering process. *Figure 42* shows the PVC pipe after drilling Well #9.

Figure 42. PVC Pipe after Drilling Well #9

Table 3 summarizes the data collected for all nine wells during drilling. Field notes for each well can be found in *Appendix G.* Exposed-Screen System B appeared to have the most success of all three systems tested.

Table 3. Data Summary of Drilling in USF GeoPark

Data Summary of Drilling in Geopark									
	Well#1	**Well#2**	**Well#3**	**Well#4**	**Well#5**	**Well#6**	**Well#7**	**Well#8**	**Well#9**
Type of System	Cased System	Exposed Screen System				Belled-End System			
Strength of Pipe	Conduit Steel	Sch20	Sch20	Sch20	Sch40	Sch40	Sch40	Sch20	Sch20
Total Depth Drilled (m)	3.5	2.2	1.4	2.5	2.35	2.2	2.3	2.1	2.32
Depth Hammered (m)	2.0	1.0	0.3	1.3	1.05	1.0	1.0	0.9	1.02
Total Drill Time (Start to Finish)	2hrs 7min	2hrs 46min	47min	1hr 19min	1hr 1min	1hr 39min	55min	1hr 23min	1hr 58min
Hammering Time	1hr 5min	11min	15min	27min	8min	15min	12min	15min	16min
Depth to Water (m)	N/A	1.98	N/A	1.26	N/A	1.43	1.55	1.90	1.52
Success or Issues	Unable to remove Drive Casing	Success (No Issues)	Lost Lower 70cm	Sleeve was pushed up	Lost well point and sleeve pushed up	Sleeve pushed up	Sleeve pushed up	Success (No Issues)	Success (No Issues)

Modifications Based on Phase I and Phase II Drilling Experiments

Several issues were faced during both Phase I and Phase II drillings. Each issue was resolved, with the exception of the problem of the breathable sleeve being pushed up. This was a constant problem during installation of both Exposed-Screen System A and Exposed-Screen System B. However, it was important to find a solution to this problem, as the breathable polyester sleeve would be a marked improvement over the lead-containing materials currently in use in Madagascar.

Fortunately, the last two drillings were successful (Wells #8 and #9). The sleeves were not pushed up, and there was no external damage to the PVC pipes. This was attributed to two factors: 1) use of shorter hammer strokes, and 2) taping and PVC cementing the end of the sleeve directly under the belled-end or PVC adapter (depending on the type of system used). The shorter hammer strikes took longer to get the pipe down;

however, there was less stress placed on the pipe and possibly the sleeve for each strike. Application of PVC cement to the edges of the sleeve prevented water from getting underneath and loosening the breathable sleeve. Also, taping *and* PVC cementing the sleeve directly under the belled-end/PVC adapter on the PVC pipe protected the taping. The belled-end and PVC adapter were larger in diameter. Therefore, there was less friction at the beginning of the sleeve as well.

Phase III – Madagascar Trials

Madagascar Exposed-Screen System

Since only the last two drillings of Exposed-Screen System B were successful, further testing was needed to confirm the resilience and reliability of that method. The next step was to try this method in eastern Madagascar. However modifications needed to be made in order to try the method in Madagascar. Thus, the Madagascar System was designed as a variation of both Exposed-Screen System A and Exposed Screen System B, and the plans were sent to Madagascar. Due to the resources available in Madagascar, one major modification needed to be made. The well-point had to be forged by a local blacksmith instead of being manufactured. Small adjustments also had to be made because of the difference between standard units to metric units. The entire system was built locally and implemented.

Installation. Two wells were installed in close proximity to each other in Tamatave, Madagascar. Both wells were cored. The first well was cored 3.1 m in 13 minutes, and the second well was cored 3.8 m in 24 minutes. During coring, soil samples were taken and examined every 1 m. The soil from the first well contained mainly white and yellow sand. The soil from the second well contained a mixture of organics and yellow sand. Detailed results can be seen in the drilling chart in *Appendix H*.

Between coring and installation of the Madagascar System, the driller hammered a galvanized iron rod into the ground in order to drill even deeper. This step was not part of the instructions that were given to him. After hammering the galvanized drive pipe, the Madagascar system was placed in the hole and hammered. The first well was hammered 1.5 m in 26 minutes and the second well was hammered 0.6 m in 39 minutes. The maximum distance that the hammer was raised before striking the brick was 70 cm. This was the same distance for both wells.

The driller did not initially use the galvanized iron (GI) drive pipe to hammer the Madagascar system into the ground. Instead a brick was placed on top of the PVC pipe, and the brick was hammered. The brick was used as a buffering device to hammer the PVC pipe into the ground. This process of hammering the brick onto the PVC pipe was not part of the instructions sent to the driller. This was believed to have happened due to translation errors. It was meant for the driller to insert the GI drive pipe into the PVC pipe of the Madagascar System and use the brick to hammer the GI drive pipe instead of the PVC pipe. The GI drive pipe is stronger than the PVC pipe and can endure the hammering process much better than the PVC pipe. Consequently, for both wells, the PVC pipes could not be hammered to the desired depth, and drilling was put on hold. Corrected instructions for the hammering process were sent to Madagascar, and the driller completed the hammering process for both wells by inserting the GI drive pipe inside the PVC pipe and hammering the GI drive pipe. However, this hammering process was delayed a few days due to poor weather conditions and prior commitments for the driller. Based on field data (video, photos, and notes) sent from Madagascar, the correct hammering process worked well.

Deconstruction. Almost one week passed before the wells were deconstructed. Both wells were deconstructed and removed from the ground without any issues. The well-points for both systems were left in the ground, and the PVC pipes and GI drive pipes were examined. The breathable sleeves on both wells did not appear to have any damage and were not pushed up. The breathable sleeves were then removed and the slots on the PVC pipes were examined. Just like Wells #8 and #9 in Phase II, there appeared to be no damage to PVC pipes or the GI drive pipes. The PVC pipes of the deconstructed systems can be seen in *Figure 43 and Figure 44*.

Figure 43. PVC pipe of Well #1 of the Madagascar System

Figure 44. PVC pipe of Well #2 of the Madagascar System

Discussion of Drilling Alternatives

Lessons Learned from Phase I and Phase II Drilling

Based on the results of the testing performed at USF's GeoPark during Phase I and Phase II drilling, a number of conclusions may be made. Of the three methods tested during Phase I and Phase II drilling, the method that worked best under the parameters outlined for this study was Exposed-Screen System B, a modification of Exposed-Screen System A. The main advantages of Exposed-Screen System B were its simple design, the amount of equipment required, and cost-effectiveness. Exposed-Screen System B was designed so that the neck (end closest to the well-point) of the PVC pipe could be strengthened for the hammering process. In turn, this required fewer parts in the system. The only equipment required to build the system was a breathable sleeve, four screws, an extra piece of PVC pipe, and a well-point. No welding was required. As a result, this made building Exposed-Screen System B easier, faster, and more cost-effective.

Exposed-Screen System B cost approximately US$16 to US$18 per well, depending on the type of PVC pipe preferred. This was a more cost-effective system than the Cased System, which costs about US$20 and Exposed-Screen System A, which ranged from US$20 to US$23 depending on the preferred PVC pipe. The complete cost breakdown of each well can be found in *Appendix I*. These prices include only the costs of materials and drilling equipment. It does not include the cost of hiring a driller and/or any other possible overhead costs. Also a drilling equipment fee was included per use/well based on an expected lifetime of 20 uses.

The best technique for keeping the sleeve in place was to attach the breathable sleeve directly under the belled-end or PVC adapter (depending on the system) using PVC cement. The PVC cement helped secure the breathable sleeve to the PVC pipe by keeping water from getting underneath the screen and detaching it from the PVC pipe. All drilling attempts using this technique were successful. Other techniques that were believed to be helpful included: wrapping electrical tape around the ends of the breathable sleeve; wrapping fishing line around the length of the sleeve to help hold the sleeve to the PVC pipe; and cutting notches above and below the slots in the PVC pipe to give the fishing line better grip.

The best technique for protecting the PVC pipe and other parts of the drilling systems from damage during drilling was shorter hammer strokes. With shorter strokes there is less pressure per stroke being exerted on the system. This helps protect the system from breaking at the weaker points during the hammering process. Shorter strokes may also contribute to protecting the breathable sleeve from being pushed up. For two out of the three wells that were drilled using shorter strokes, the sleeve was not pushed up. In the only well that had the sleeve pushed up, the sleeve was only pushed up about 0.25 m. This was an improvement compared to the other wells with sleeves pushed up. The benefits of shorter strokes also presents disadvantages. Shorter strokes mean longer drilling times, because less force is being exerted and the system is not being driven down as far per stroke. Most of these recommendations were included in the instructions sent to Madagascar for assembly of the Madagascar System.

Lessons Learned from Madagascar Drilling

In designing the Madagascar System, the goal was to test a prototype similar to Exposed-Screen System B. The key modification made to Exposed-Screen System B so that it could be used in Madagascar was the well-point. In hindsight, the well-point should have been forged (instead of purchased) for Phases I and II in order to further understand and better mimic drilling conditions in eastern Madagascar.

The two well drillings in Madagascar were successful. Well-points for both systems were left in the ground due to the design of the system. There were no problems during the drilling of the two wells, and there was no damage on the exterior of either system that was installed. Additionally, after removal, the breathable sleeves appeared to be in place, just as they were before installation. This could be largely due to the PVC cement that was applied to both the top and bottom of the screen to secure it to the PVC pipe.

The cost of materials for each well (drilling 6 m into the ground) in Madagascar was 38,850 Ariary (currency in Madagascar), which is equivalent to approximately US$14. This does not include the driller’s fee. The cost of materials to drill a well in Madagascar using the current drilling method is 50,000 Ariary, which is about US$18 per well. That is over 20 percent savings when comparing the Madagascar System to the current drilling method in Madagascar. This is a considerable savings in a country in which over 80 percent of the population live on less than US$1.25 per day (UNICEF, 2013). The cost of materials for both drilling methods can be found in *Appendix J and K*, respectively.

The main issue encountered in the Madagascar drilling was unclear or mistranslated communication. Both the assembly and drilling instructions had to be translated twice, from English to French, then from French to Malagasy. Moreover, the instructions were passed through four people, increasing the chance for error in communicating. The best solution would have been direct communication and personal oversight of the drilling. However, despite the communication issues the two well drillings ended up being successful.

CHAPTER 5. CONCLUSIONS & RECOMMENDATIONS FOR FURTHER STUDY

Conclusions

In eastern Madagascar, Pitcher Pump systems, which contain leaded components in the drilling equipment, are widely used. As the ingestion of lead in any form can be harmful to humans, previous attempts have been made to remove the lead from the pump components. The purpose of this study was to successfully remove the lead from the drilling equipment by developing a cost-effective alternative drilling method that uses lead-free components.

Three alternative design options, the Cased System method, the Exposed-Screen System A Method, and the Exposed-Screen System B Method, were designed and tested. A total of nine wells were drilled over a span of two drilling phases at USF's GeoPark in Tampa, Florida. Of the three methods, the Exposed-Screen System B Method, a modification to the Exposed-Screen System A design, proved to be the most successful option. It was also the simplest design, required the least amount of equipment, and was the most cost-effective. However, with only two successful consecutive drillings, the decision was made to send the design to eastern Madagascar for further testing.

Several modifications had to be made due to the unavailability of certain materials in eastern Madagascar. The newly developed method was called the Madagascar System.

Despite communication errors, two wells were successfully drilled and removed for inspection using this system. There were no significant issues with the drillings.

Recommendations for Further Study

The Madagascar System, designed and tested in this study, is a promising alternative to the current drilling methods for Pitcher Pump systems in Madagascar. However, more testing needs to be performed on this new system in Madagascar to address any general issues that may arise.

A standard screen length of a 0.5 m was chosen for this study due to the shallow depths that were being drilled for each well. Well screens need to tap the aquifer zones or the water-bearing formations at the correct level (Harter, 2003). Therefore, it is crucial that an appropriate screen length be used, based on knowledge of the area and depth of the aquifer being drilled. Further research and experimentation into the appropriate screen length for various areas of Madagascar should be carried out.

During drilling and installation of wells, safety should always be a concern. During the drilling and installation of the two wells in eastern Madagascar, safety precautions were not taken and safety equipment — such as hardhats and close-toed shoes — were not worn. This could be due to a lack of financial resources and/or lack of knowledge of the safety precautions and equipment needed to stay safe. For future drilling in Madagascar, drillers and their assistants should be made aware of safety precautions and use safety equipment during drilling and installation.

In Madagascar, well-points, which are essential pieces of drilling equipment, are typically forged by a blacksmith from galvanized iron pipe. During this forging process, the galvanization is burned away, releasing zinc fumes and possibly the fumes of other metals into the air. Breathing these fumes poses a potential health risk to the blacksmith, as inhaling too much zinc oxide can cause “metal fume fever” (New Jersey Department of Health and Senior Services, 2007). The long-term effects of inhaling zinc oxide and other metals in the galvanized coating on the metal pipes in Madagascar should be further investigated.

During the Phase I drilling, the first alternative system, the Cased System, was drilled to a depth of approximately 3 m but could not be removed from the ground because it became lodged in about 0.5 m (1.5 ft) of clay. Further testing could not be accomplished, and further drilling was not performed. In a separate location, where there is no clay, another drilling attempt is recommended so that a complete round of testing can be performed with the Cased System. The Cased System could be valuable in contexts that required drilling exclusively in sandy soils.

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APPENDICES

Appendix A. Cost Estimate of All Drilling Materials

Table 4. Cost Estimate of All Drilling Materials

Drilling Materials Cost Estimate					
Tools & Materials for Phase I & Phase II	**Notes**	**Cost per Piece/ft**	**# of Pieces/ft**	**Pieces/feet**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	10	pieces	$90.50
HDX Fence Post Driver	Model # 901147HD	$27.94	1	pieces	$27.94
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	3	pieces	$0.00
1.5" Rigid Conduit Pipe	10 ft lengths	$3.61	50	ft	$180.45
1.25" Rigid Conduit Pipe	10ft lengths	$3.08	10	ft	$30.75
3/4" Rigid Conduit Pipe	10 ft lengths	$1.83	40	ft	$73.04
3/4" Rigid Drive Couplings		$1.96	6	pieces	$11.76
1" Rigid Drive Couplings		$2.80	5	pieces	$14.00
1.25" Rigid Drive Couplings		$3.50	8	pieces	$28.00
1.5" Rigid Drive Couplings	Included with purchase of Rigid Conduit Pipe	$0.00	5	pieces	$0.00
Schedule 20 160 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths - Total 40 ft	$0.25	40	ft	$10.00
Schedule 20 200 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths - Total 40 ft	$0.27	40	ft	$10.80
Schedule 20 200 psi PVC Pipe	1" PVC Pipe - 10 ft lengths - Total 10 ft	$0.17	10	ft	$1.68
Schedule 40 370 psi PVC Pipe	1.25" PVC Pipe - 10 ft lengths - Total 20 ft	$0.55	20	ft	$11.02
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft	$0.00
1.25" PVC Adapter	Sch 40 Adapter	$1.13	8	pieces	$9.02
1" PVC Adapter	Sch 40 Adapter	$0.93	5	pieces	$4.64
Pan Head Screws	100 pieces per box	$4.98	1	pieces	$4.98
PVC Cement		$4.87	1	pieces	$4.87
Breathable Polyester Sleeve	Borrowed from USF	$0.00	25	ft	$0.00
Plumbers Tape		$4.27	1	pieces	$4.27
Electrical Tape		$1.97	1	pieces	$1.97
Fishing Line	From Mercer University	$0.00	1	pieces	$0.00
Tools & Materials Used in Madagascar	**Notes**	**Cost per Piece (tube)**	**Estimated Number of uses for equipment/materials**	**Equipment Fee based on uses per well**	**Total Cost**
Pressure PVC Pipe	6 m lengths - Pressurize Pipe- 28mm x 32mm	$9.94	1	$9.94	$9.94
Galvinized Iron Pipe	6 m lengths - 15mm x 21mm	$7.59	20	$0.38	$0.38
Galvanized Iron Point	GI pipe forged into a point by a local blacksmith	$0.35	1	$0.35	$0.35
Galvanized Iron Coring Tool	6m - 15x21mm drive pipe welded to 0.1m - 26x24mm pipe	$10.36	20	$0.52	$0.52
Breathable Sleeve	100% Polyester - 1 m	$1.38	1	$1.38	$1.38
Electric Tape	20m roll	$0.31	2	$0.16	$0.16
Fishing Line	25m roll	$1.04	2	$0.52	$0.52
PVC Cement	15cm tube	$4.14	6	$0.69	$0.69
TOTAL					**$533.62**

Appendix B. Soil Survey

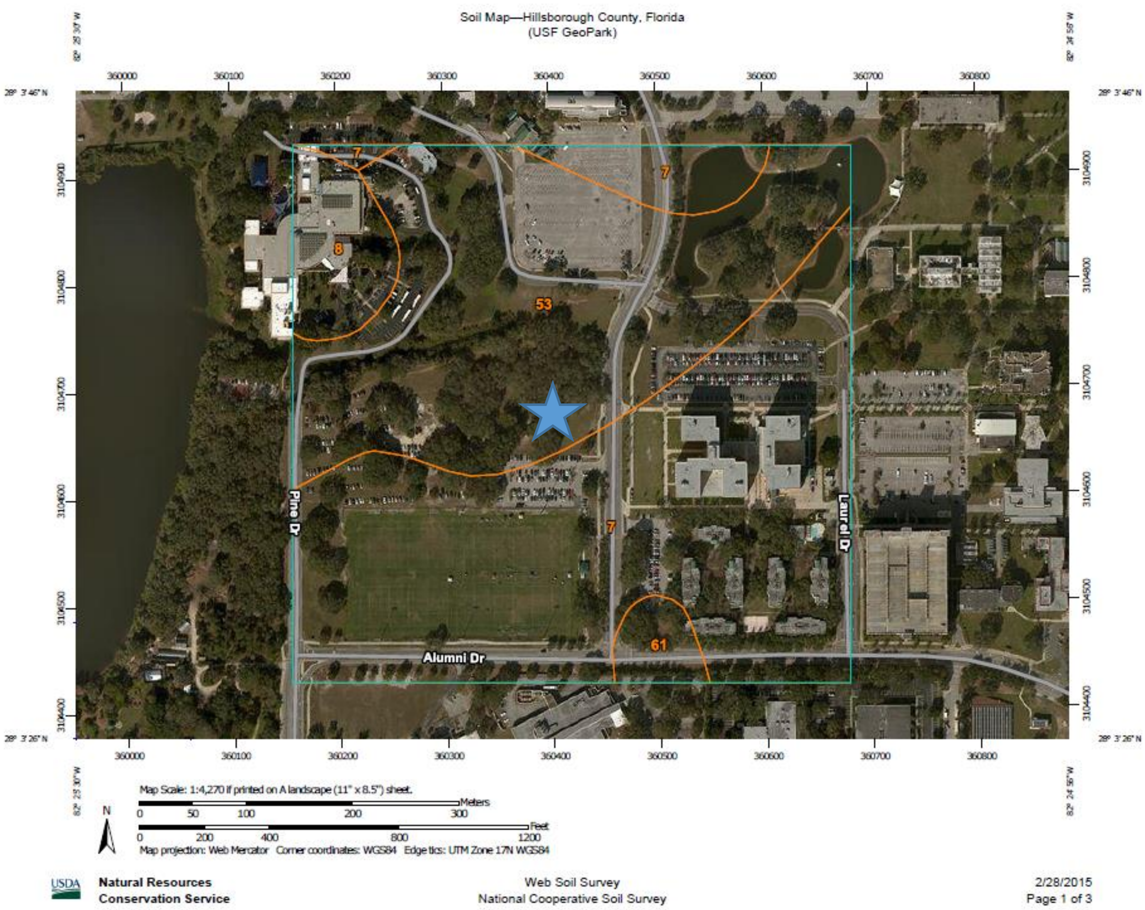
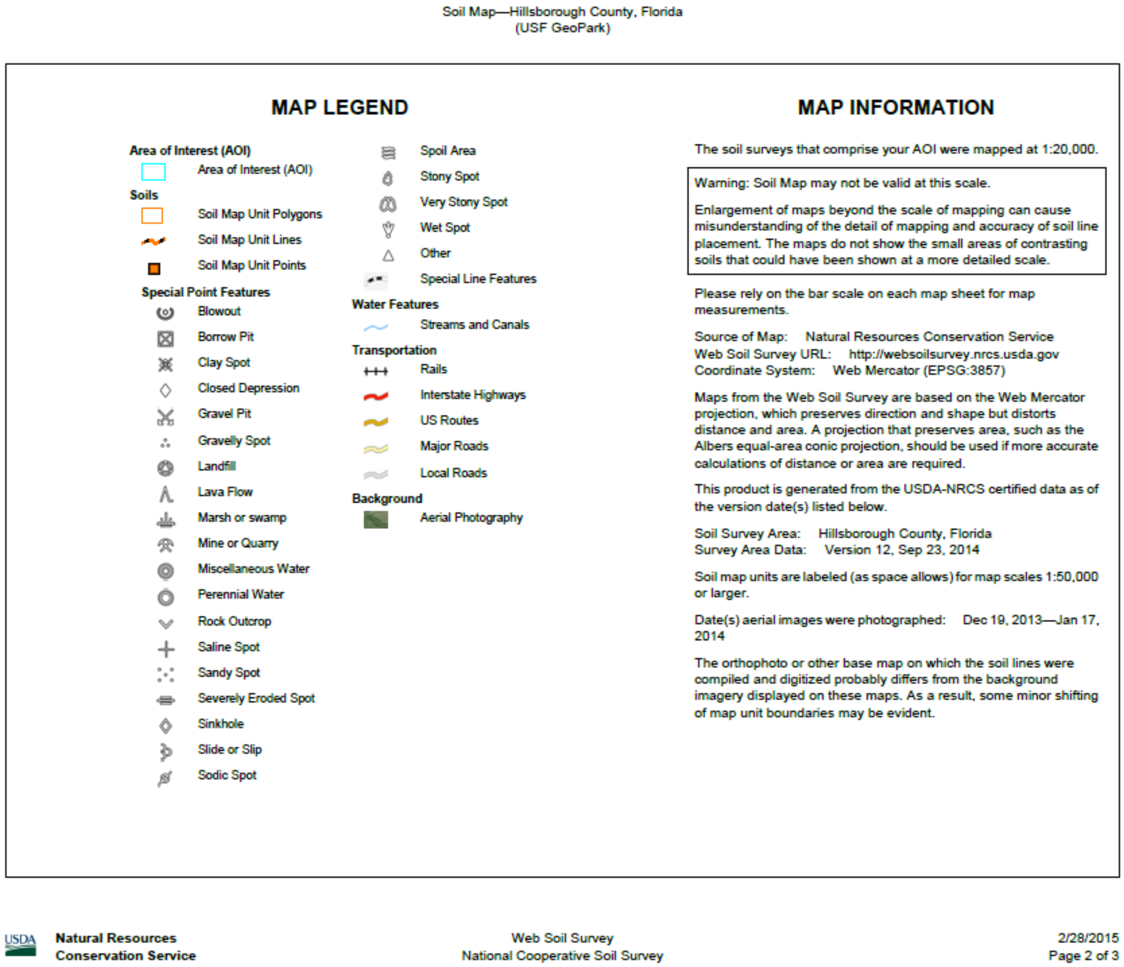


Figure 45. Soil Map of GeoPark



Soil Map—Hillsborough County, Florida
(USF GeoPark)

MAP LEGEND

Area of Interest (AOI)
Area of Interest (AOI)

Soils
Soil Map Unit Polygons
Soil Map Unit Lines
Soil Map Unit Points

Special Point Features
Blowout
Borrow Pit
Clay Spot
Closed Depression
Gravel Pit
Gravelly Spot
Landfill
Lava Flow
Marsh or swamp
Mine or Quarry
Miscellaneous Water
Perennial Water
Rock Outcrop
Saline Spot
Sandy Spot
Severely Eroded Spot
Sinkhole
Slide or Slip
Sodic Spot
Spoil Area
Stony Spot
Very Stony Spot
Wet Spot
Other
Special Line Features

Water Features
Streams and Canals

Transportation
Rails
Interstate Highways
US Routes
Major Roads
Local Roads

Background
Aerial Photography

MAP INFORMATION

The soil surveys that comprise your AOI were mapped at 1:20,000.

Warning: Soil Map may not be valid at this scale.

Enlargement of maps beyond the scale of mapping can cause misunderstanding of the detail of mapping and accuracy of soil line placement. The maps do not show the small areas of contrasting soils that could have been shown at a more detailed scale.

Please rely on the bar scale on each map sheet for map measurements.

Source of Map: Natural Resources Conservation Service
Web Soil Survey URL: http://websoilsurvey.nrcs.usda.gov
Coordinate System: Web Mercator (EPSG:3857)

Maps from the Web Soil Survey are based on the Web Mercator projection, which preserves direction and shape but distorts distance and area. A projection that preserves area, such as the Albers equal-area conic projection, should be used if more accurate calculations of distance or area are required.

This product is generated from the USDA-NRCS certified data as of the version date(s) listed below.

Soil Survey Area: Hillsborough County, Florida
Survey Area Data: Version 12, Sep 23, 2014

Soil map units are labeled (as space allows) for map scales 1:50,000 or larger.

Date(s) aerial images were photographed: Dec 19, 2013—Jan 17, 2014

The orthophoto or other base map on which the soil lines were compiled and digitized probably differs from the background imagery displayed on these maps. As a result, some minor shifting of map unit boundaries may be evident.

USDA Natural Resources Conservation Service
Web Soil Survey
National Cooperative Soil Survey
2/28/2015
Page 2 of 3

Figure 46. Map Legend of Soil Map of GeoPark

Map Unit Legend

Hillsborough County, Florida (FL057)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
7	Candler fine sand, 0 to 5 percent slopes	35.1	53.8%
8	Candler fine sand, 5 to 12 percent slopes	3.5	5.3%
53	Tavares-Millhopper fine sands, 0 to 5 percent slopes	25.2	38.7%
61	Zolfo fine sand	1.4	2.2%
Totals for Area of Interest		**65.3**	**100.0%**

Figure 47. Map Unit Legend of Soil Map of GeoPark

Appendix C. Materials List and Construction Directions in French

Table 5. Materials list and Construction Directions in French

Construction / Installation d'un puit PVC (avec technique modifie)

	Materiels/Outils necessaire	Unite	Quantite	Commentaire
1	Tuyaux Galva, Chine -- 15 X 21 mm	barre de 6m	1	
2	Marteau pour frapper le tuyaux galva	marteau or tuyaux	1	utilise le meme chose que toussaint utilise pour installe les forages de Pompe Tany
3	Scie pour couper les tuyaux PVC	scie	1	
	Materiaux de puit/forage			
1	Tuyaux Galva, Chine -- 33 X 42 mm	morceau de 0,40 m	4	ces tuyaux sont pour fabrique les "points" - peut-etre acheter une barre de 3m ou 6m, et Toussaint peux les couper
2	Tuyaux PVC, qualite PRESSION -- 28 X 32 mm	barre de 6m	4	avant d'acheter, on faux confirmer que ce tuyaux PVC peut "entrer" dans le tuyaux Galva 33 X 42
3	tissue polyester, pour couvrir les crepines	metre	quelques	le meme qualite de tissue qu'avant, il faut etre "respirant" -- pour laisser l'eau passe
4	colle PVC	boite	1	
5	scotch electrique	rouleau	1	
6	ligne de pêche	rouleau	1	on va utiliser ca pour "bien connecter" les chausettes sur les tuyaux PVC

Taches de travail

A **Achete les materiaux/materiels necessaires** (peut-etre Toussaint a quelques outils deja?)

B **Construction des "Points"**

Toussaint peux envoyer les morceaux de tuyaux galva (0,40m) chez son ami le forgeron, pour preparer les "points" comme avant (regarde le photo a cote)

C **Coudre les "chausettes" pour le filtre**

Tu peux passer la commande avec le tailleur pour coudre "les chausettes" qui faux attacher bien (serré) sur les tuyaux PVC de 28 X 32mm. On veux avoir 5 chausettes de 1 metre longeur par chausette.

Explication d'installation

- je vais envoyer les detailles specifiques pour les installations des forages plus tard, mais, en breve, ca que nous voulons faire est de:

1) couper les crepines sur le Tuyau PVC Pression, et bien attache le chausette sur le tuyau (pour completement couvrir les crepines)
2) mettre le tuyau (cote bas, avec crepine/chausette) dans le "point" (tuyau galva)
3) craisser le trou jusqu'e au niveau de nappe d'eau (comme Toussaint fait toujours pour les systemes de Pompe Tany)
4) inserer le "point" avec son tuyau PVC dans le trou
5) inserer le tuyau galva de petit diametre (15X21mm) a l'interieur de tuyau PVC Pression (pour que ca descende en bas, jusque ver le parti pas de l'interieur du "point")
6) bien tapper sur le tuyau galva de 15X21mm, pour que le point et son tuyau PVC pression descende, jusqu'au niveau final qu'on veux pour le forage
7) enlever le tuyau galva de 15 X21mm

ON ESPERE QUE CA VA MARCHER! NOUS ALLONS VOIR :-)

Appendix D. Assembly Instructions for the Madagascar System in French

Préparation de Tuyau PVC

1. Coupe 50cm d' une cote de tuyau PVC de 6m (pour que le longeur total est 5m et demi).
2. Pour les fentes coupées:
    a. Mesures 40cm de cote bas de tuyau PVC. A 40cm marque, en utilisant un scie, fait les fentes coupées en diagonalle chaque 2 cm pour 10cm (c'est a dire, 5 fentes coupées). Voir photos ci-dessous. (NOTE: Fait attention que les fentes sont seulement ¼ or 1/3 du diametre du tuyau – PAS PLUS que ca, or le tuyau va devenir trop faible) Apres avoir fait les premieres 5 fentes, tourne le tuyau un demi-tour (180 degrés), laisse une espace de 2cm, et continuer a faire encore 5 fentes (toujours chaque 2 cm). Alors, tourne encores 180 degrés, et fait le meme chose, jusq'ue qu'on a un longeur de 50cm de tuyau avec les fentes a un cote ou l'autre.

    Après avoir coupe tout les fentes, etre sur de bien brousser les fentes, pour enlever les petits morceaux coupe de PVC quie peut deranger la fabrique pendant l'installation.

3. Ensuite, coupe une petit epaisseur ("coupure") sur le tuyau a 10cm en bas des fentes, et aussi 10cm en haut des fentes. ATTENTION de ne pas couper trop sur l'epaissure. Ces marques sera utilize pour bien attacher le fil de peche qui va proteger la fabrique bien sur le mur exterieur du PVC.

4. Une fois que les coupures ont été faites et les fentes ont été coupés, faites la chaussette de fabrique respirante sure la 0.5m de coupes. Démarrez le chausette 10cm au-dessus du haut de la plus couper. Le chausette devra être PVC collé au sommet. Ensuite, mettre la chausette vers le bas après les coupes à 20 cm au-dessous du fond plus couper, et enlever/couper le fabrique excès. Collez ensuite cette extremite. Utilisez la colle uniquement sur les extrémités. Ne pas coller ne importe où dans les coupes. Attendez que la colle PVC sécher.
5. Des que le colle a secher, bien attacher le fil de peche sur le petit epaisseur coupe, et ensuite tourner ca autour le diametre de tuyau, en montant le tuyau comme dans les photos ci-dessous , jusqu'au niveau de l'autre coupure en haut des fentes, et bien attache la.
6. Attache du scotche electrique sur les deux epaisseur ou le fil de peche est attache (NE PAS mettre du scotche sur des fentes coupee).

Preparation Final

1. Mettre le Point Du Tuyau Galva 33X42mm sur le cote bas du tuyau PVC
    a. TEST: monter le tuyau PVC sur la terre (dans l'air), en position vertical, avec le point en bas. SI le point se detache lui-meme, il sera necessaire d'inserer quelque chose (comme du papier ou morceau de fabrique) entre le point galva et le tuyaux PVC, pour que ca ne detache pas facilement. MAIS on ne veux pas mettre du chose permanent (comme le colle) ici, parce que avec ca la vibration du point galva pendant l'installation va deranger le tuyau PVC.

2. Forer le trou jusqu'au niveau de nappe d'eau (comme d'habitude pour la Pompe Tany.
3. Inserer le tuyaux PVC avec son Point galva en bas, dans le trou
4. Ensuite, inserer le tuyau galva 15/22mm a l'interieur de tuyaux PVC 28/32mm. Etre sur que le tuyau galva 15/22mm entre jusq'ue en bas, pour que ca contacte bien l'interieur du point galva. Pour tester, on peut faire monter le tuyau galva 15/22mm, quelques cm, et laisse tomber, pour ecouter que c'est "galva sur galva".
5. Commence a tapper/installer. . . Fait attention de ne pas utiliser trop de force, comme les grandes vibrations risqué de deranger le tuyaux PVC, particulierement le partie en bas avec les fentes coupees.

Appendix E. Installation Instructions for the Madagascar System in French

Photo 1 et 2: Tuyaux PVC, pret avec son filtre bien attache, et son point en bas

Photo 3 (gauche): en train de mettre le point de tuyau dans le trou (qui est deja craisse jusque au niveau de la nappe. **Photo 4 (droite):** apres le tuyau est installe jusque a la nappe – on mets le petit tuyau galva (15/22mm) dans le tuyaux PVC.

Photo 5 (gauche): actuellement, le petit tuyau galva est deja dans le tuyau PVC

Photo 6 (droite): Nous avons utilise un marteau different (le rouge) pour notre installation, mais Toussaint peut faire comme il fait d'habitude. . .

Photos 7 et 8: Tappe le marteau sur le tuyaux galva 15/22mm, qui est installe jusq'ue au niveau de point galva, a l'interieur de tuyaux PVC


Photo 9 (gauche): Presqu' a la fin de l'installation du forage!

Photo 10 (droite): Apres avoir installee le forage autours de 1 metre et demi (ou mieux 2 metres) dans le sable, on enleve le tuyaux galva 15/22mm! (DERNIER ETAPE, POUR LE MOMENT)

Appendix F. Deconstruction Instructions in French

Merci pour les videos, ainsi que ton email avec l'explication du travail. Je pense que ce processus peut bien marcher quand tout l'installation est fait dans la meme journee - je crois que le difficulte avec le 'tappage' du tuyau etait a cause de retard de temps entre la premiere partie (installation jusq'ue au niveau de nappe phreatique) et le deuxieme etape ('tappage'). . . Je pense que le retard du temps, plus les grands pluits, avaient fait que le sable s'attache bien a cote du tuyaux PVC (en haut de la nappe) – qui rend plus dificile que le tuyaux PVC descend. . . Mais c'est le recherche – et nous apprennons beaucoup! J Nous sommes content avec votre travail, et nous sommes impatients de continuer avec des prochaines etapes!

PROCHAINE ETAPE

Processus de déconstruction

** Faites ce processus pour chacun des deux puits PVC deja installées

1) Prenez des photos de chaque puits avec les tuyaux installées

2) Prenez des photos de tuyau galva de 15x22 y compris des photos en gros plan de tout dommage sur la tuyau qui etait peut-etre un peu détruit au cours du processus de 'tappage'

3) Retirez le tuyau PVC à partir du sol
   - Laissez le point dans la terre (je pense que c'est trop dificile a enlever)
   - Prenez des photos de tuyau PVC étant sorti du terre

4) Prenez des photos rapprochées de tuyau PVC toute de suite après être sorti du terrain
   - Prenez des photos de tissu filtrant (chaque cote) et tout la longeur du tuyau PVC
   - Prendre des photos rapprochées de tout dommage externe, en particulier lorsque le tuyau PVC etait en contact avec le point galva (en bas de la tissu filtrant)

5) Lavez le tissue filtrant et puis prendre des photos rapprochées

6) Enlevez le tissue filtrant du tuyau PVC et prendre des photos des fentes sur le tuyau PVC

7) Prenez des notes de toutes les grandes choses qui se démarquent (sur le tissu filtrant, le PVC inclu les fentes, le tuyau galva)

IMPORTANT: Ecris-moi un email court des que tu recois ce message – et m'explique quel jour tu esperes faire ce prochaine travail avec Toussaint.

Appendix G. Daily Journal of Preparation before Drilling

12/1/14

Welded extra weights onto the **drive hammer**. First had to sand down the red paint on the fence post driver. Then located 2 square steel rods. Had to cut them to size to fit the height of the fence post driver. Also sanded down the rust off of the metal bars so that we could weld them to the driver. Finally took the fence post driver and the 2 bars into the welding shop and mig welded the two bars (opposite sides of each other to counterbalance the weight) to the fence post driver. Total weight of fence post driver is a little over 21 pounds. Metal bars were slightly over 3lbs each. Approved by Dr. MacCarthy.

12/2/14

Discovered that the **stainless steel will weld to the galvanized steel**. Tested this by welding small well point (1.620") to a piece of the 1.5" (actually 1 5/8") steel conduit pipe. Before welding, had to sand the galvanized portion off of the steel. Then tested the weld by hammering the welded piece into the ground a couple of times. Totaled about 30 hits on the welded piece. It went crooked but the welds never broke. See picture…

Spoke with MacCarthy and Mullis about whether should go with smaller diameter well point or larger diameter well point. Options: 1) Weld a steel plate with the same diameter as the OD of the 1.5" steel pipe to the smaller well point so that it does not end up being pushed back up into the pipe. The smaller diameter well point is actually too small for the 1.5" steel pipe. 2) Shave down the larger well point so that the OD of the well point is the same as the OD of the 1.5" pipe.

Decided to shave down the larger well point from over 2 inches to about 1.9 inches, which is the same as the outer diameter of the 1.5 inch rigid conduit pipe. It is easier than building a steel plate for the smaller well point and the nub is larger for welding a drive coupling to. Will need to shave down at least two more large diameter well points.

12/3/14

Shaved down 2 more well points to about 1.9 inches (OD). Decided to use a PVC adapter to connect the coupling to the PVC pipe. Otherwise, according to Mr. Mullis, it would not be possible to thread the PVC piping because it is so thin. Therefore, I created the bottom attachment pieces for each system (exposed and closed). Had to buy 1" and 1.25" PVC adapters from CMC Supply. For the exposed system, welded the 1.25" coupling to the shaved well point and then screwed the 1.25" adapter into the coupling. (Note: noticed a white substance on the inside of the coupling after welding it to the well point) The PVC adapter screws into the coupling on one side but allows the 1.25" PVC pipe to slide in on the other side. Had to grind down the welds a little to smooth them out. Performed the same setup for the Cased System so that the attachments will fit into the outer drive casing (1.5”). Fitted both end attachments on the respective size piping and they both fit pretty well! Will need to shave down the PVC adapter a little more on the exposed screen attachment so that it is flush with the well point diameter as the pipe is being driven down.

Tomorrow’s goal – make a total of three attachments for each system, and further thread the steel piping at Home Depot.

12/5/14

Made Home Depot run to further the threading in the piping so that the drive couplings would fit. Took 2 hours.

12/8/14

Made remainder of copies of the well points made 3 for the 1” and 3 for the 1.25”

12/9/14

Did nothing because of Drug Test

12/10/14

Finished boring out the drive cap. Made 2 drive caps. One is bored a little deeper than the other for stability. Spoke with Dr. McCreanor who suggested that we use pipe buffers so that the threads in the pipes do not get messed up. Made preparations to cut slits in the PVC pipes. Traced the pipes with permanent marker. Took a LONG time, and it is hard to draw straight lines on round pipe.

12/11/14

Finished making preparations for Tampa trip. Made slits in the PVC pipes, both 1” and 1.25”. Also cut and made short buffer pipes for the SS ¾” and the 1.5” pipes for when they are being hammered into the ground.

1st Trip to Tampa – Phase I

12/12/14

Drove down to Tampa. Forgot the Auger. Made different arrangements to auger. Will now work on boring the wells tomorrow. Plan on drilling a total of 4 wells.

12/13/14 – FIELD NOTES

WELL #1 - Using Cased System Method

8:00 AM Arrived on site and assessed the site and prepared for drilling

9:20 AM Began Boring with 1.5" PVC Pipe – took sample of top soil – Fine sand – black, has organics

9:30 AM Bored 100 cm – took sample – fin, gray sand, clumpy

9:37 AM Reached 145cm – sand turned muddy (possibly at the top of the water table), light gray sand

9:40 AM Reached 150cm – similar to previous sample, little less muddy. At this time stopped boring and preparing for percussion well point drilling. Stuffed the well point with paper to make sure it would not fall out of the drive casing as it was being set into the hole. Forgot to use plumbers tape on threads before connecting to the drive coupling. Also marked off the drive casing so would know how far it's being driven down.

10:22 AM Inserted 10' drive casing and commenced hammering at 1.4m (some of the wall caved in after pulling out 1.5" pipe for the boring). This 1.4m DOES NOT include length of well point at bottom. Measurement is down to the PVC adapter. **It's an extra 11cm if drive coupling and well point are included.**

10:25AM 1.8m down

10:28AM 2.0m down

10:33AM 2.2m down

10:38AM 2.5m down

10:45AM 2.55m down. Paused to extra add 5.0' drive casing. **Examined 1st connection between the drive coupling and the buffer pipe and first 10.0' pipe. That connection is bent; however, the buffer pipe was able to be unscrewed out of the coupling. Did not try to unscrew other side of drive coupling.

11:00AM Added 5.0' section of drive casing (this time added plumber's tape to both sided of the 5.0' section of piping.

11:05AM Started hammering

11.08AM 2.8m down

11:20 AM 3.2m down

11:27AM 3.4m down - from ground to end of pipe **Stopped here to add in the 1" PVC inner casing. Noticed the threads are really messed up at the top of the pipe between the buffer pipe and the drive coupling. The threads were also damaged between the drive coupling and the 5' pipe at the top; however was able to remove the coupling from the 5' pipe with 2 pipe wrenches.

Added screen sleeve to the 1" PVC pipe and had to add a belled end to one end of the PVC pipes using a torch. PVC glued the 2 10' sections together

12:55 PM Inserted PVC Pipe. It went in and screwed in smoothly. No problems with attaching the 1" PVC pipe to the well point.

1:05PM Tried removing outer drive casing, but could not get the drive casing out of the ground. Tried using leveraging to get the pipe out of the ground and ended up bending the steel pipe that we were using for leveraging. Problem could be that the piping is too far down in the ground. Also the friction from the soil could be causing the problem

Method #1 - Project on hold…

Was not able to take depth to water or bottom of well to top of pipe…

Well #2 - Using the Exposed-Screen System A Method

2:00PM Began boring well #2

2:05PM down 40cm – collected sample, smooth sand with mixture of organics

2:12PM Down 105cm – sample similar to last sample

2:20PM Down 135cm – collected sample - sand becoming more muddy. Paused for lunch and to prepare for well point drilling

Break for lunch

Placed sleeve around the screen

Made more modifications????

Belled the end of the first PVC pipe with a torch.

4:35PM Started hammering at 1.1m **(some of the well wall collapsed in)

4:37PM Down 1.4m

Break

4:42PM Still 1.4m

4:45PM Down 1.9m

4:46PM Down 2.1m

Stopped at 2.1m. At this point we are 0.5m into the water table. Did not want to go down too far for fear that we would not be able to get the pipe out of the ground. (**Normally we would leave this pipe in the ground but have no permit and we need to remove all piping from the drill site.)

5:15PM Successfully pumped water out of the exposed screen system using a PVC pipe with a one-way check valve.

5:30PM Successfully removed the pipe from the ground.

***Top of pipe to water table – Depth to water – 6.5ft

***Bottom of well to top of pipe – 7.9ft

12/14/14

Well #3 – Using Exposed screen method

8:05 AM – Tried boring hole but hit root

8:18 AM Began boring 3rd well

8:20AM – 10cm – took sample – contained fine sand with organics

8:28AM – 50cm – took sample – damp, mixed with organics (black) and light gray sand

8:40AM – 135cm – took sample, very moist sand but not quite muddy. Still has some organics.

**Stopped at this point to hammer

8:50AM – 100cm –must have been some cave in. **Used same pipe that was used in well#2 the day before

9:05AM – 130cm – Problem: Lost lower 70cm of pipe. Broke at the first slot in the screen. Clean break.

**Thoughts: There were three sets of slots that were made in the pipe. The slots had little stability between each set of slits

**70cm is still stuck in the ground. Couldn't fish it out.

Well #4 – Exposed Screen System

11:18AM – started boring

11:23AM – 1st sample. Sandy soil with organics. Dark color, small clay pieces

11:30AM – 2nd sample – mostly sand, light color.

11:34AM – 3rd sample – mostly sandy

11:37AM – Ended coring at 110cm

12:10PM – began hammering at 100cm; however, PVC pipe was too long and had to modify so that there was enough distance between the drive hammer and the PVC pipe

12:12PM – Recommenced hammering

12:15PM – Paused at 2m down to take measurements:

Depth to water from top of pipe – 6.95ft

Top of pipe to the bottom – 7.2ft

0.25ft of water in the pipe

Break

12:35PM – recommenced hammering

12:37PM – 2.4m down - Stopped drilling at 2.4m down

12:40PM – Took another measurement:

Depth to water from top of pipe – 5.75ft

Top of pipe to the bottom – 9.2ft

3.45ft of water in the pipe

***Pipe is about 0.46m (1.5ft) above the ground*

Lunch Break

2:10PM – *took another depth to water reading – 5.65ft*

2:20PM – Pulled pipe out of ground

Sleeve was pushed up. This seemed to happen as the pipe was being hammered down

Thoughts: sleeve was made for 1.5" pipe, but we used it on 1.25" pipe. Need smaller sleeve. Also maybe make notches at top and bottom of screen to help hold screen in place.

**Note: this is schedule 20 pipe

Well #5 – Exposed screen system

2:33PM – Began coring

2:50PM – 1st soil sample at 0.5m

2:57PM – 2nd soil sample at 0.8m

3:19PM – 3rd soil sample at 1.2m

3:25PM – stopped coring at 1.25m

3:56PM – Began hammering at 1.1m (slight cave in)

4:00PM – down 1.7m from ground (not top of pipe)

4:03PM – down 2.2m from ground (not top of pipe)

4:04PM – down 2.25m from ground (not top of pipe)

**Problem: Pipe broke off at the threads of the adapter that screws into the drive coupling and well point

** Also tried the screen with having grooves at the bottom of the pipe and putting the fishing line in the grooves and the top slit of the PVC pipe; however, the screen still slid up the pipe just like the last well.

Note: This well used schedule 40 (NOT sch 20) 1.25" PVC piping.

Also added a longer section of metal drive ¾" pipe since we used the full 3m (10ft) of PVC pipe so that the drive hammer would not hit the PVC pipe and crush it

This well head is still in the ground…

Preparation before 2nd trip to Tampa

12/22-12/23/14

Tapped I-bolts into 2 of the well points in the machine shop

12/29/14

Created new prototype for Tampa.

Used the belled end of sch20 200psi/sch40 370psi and inserted about 3.25" of sch20 160psi into the belled end of the sch20 200psi/sch40 370psi PVC pipe. Then drilled four holes and screwed in four 3/8" self-drilling screws 1cm inward from the end of the belled end. Had to cut the tips off each screw in order for them to fit through the PVC and into the spacing of the well points.

Inserted the well point. Need to make two sch 20 and two sch 40 PVC pipes. Today, made two prototypes with sch 20 PVC pipe and one sch40 PVC pipe.

12/30/14

Made a belled end for the last sch40 PVC pipe. Noticed that this particular belled end is wider than the diameter of the well point so I filed down the edges of the well point to make it smooth between the well-point and the belled end.

2nd Trip to Tampa, FL – Phase II

January 4, 2015

Traveled to Tampa, tons of rain and traffic!

January 5, 2015

Attempted to remove all three wells that were still in the ground from last trip. **Removed well #3** (last 70cm of pipe) from the ground. Did this by augering down to the tip of the 70cm pipe. Then we used a belled out end of a 1.25" pipe and fit it to the end of the 70cm pipe and twisted and turned and pulled the end of the pipe out of the ground.

January 6, 2015

Attempted to remove last two well points (well #1 & well #5) from the ground. *Slight setback due to stolen phone.*

Well#6 – Exposed-Screen System B

***NOTES – Schedule 40 PVC**

-Need ear plugs when drilling

-No Rubber was used on the inside of the drive cap for this round of drillings

9:11am - Began coring for Well #6 with 1.5" PVC pipe

9:20am – stopped to cut 1.5" PVC pipe to adjust for height for Monica

9:43am – Sample taken at 0.5m down

9:48am – Sample taken at 1.0m down

10:12am – Sample taken at 1.25m down

10:15am – Stopped Coring

*****From this point, measurements are taken from the end of PVC pipe to ground level. Need to add on 5.5cm for the well point***

10:35am – Started hammering at 1.15m

10:39am – Mike stopped at 1.43m and Andrew started

10:42am – 1.7m (Andrew)

10:44am – 1.93m Andrew stopped, Monica started

10:46am – Reached 2 meters

10:50am – Reached 2.15m total depth and stopped hammering

**Issue with removing the ¾" steel drive pipe from inside the 1.25" PVC pipe. It appears to be stuck at the shorter section of the ¾" drive pipe that sits above the well point. Know this because were unable to unscrew the ¾" pipe out and remove that pipe including its coupling.

Pouring a bucket of water to fill the PVC pipe and attempting to remove the 3/4" pipe didn't seem to work either

11:12am – Pulled again and this time pulled out inner drive pipe. As it was pulled out, it felt like it was being pulled out of sand.

****___Checked Depth to Water___ *– 7.5ft (top of pipe to water level) – 2.8ft (top of pipe to ground level) =4.7ft or 1.43meters.*

11::45am – Pulled PVC pipe out of ground. SUCCESS!

NOTES

- **Pulled PVC pipe out of ground. SUCCESS!**
- **Drilled (hammered) a total of 1.0m**
- **Sleeve used is actually the right size screen for 1.25" pipe**
- **Sleeve for screen was moved (slid down to belled end of pipe) during drilling and removal. Next drilling will start sleeve immediately after belled end.**
- **PVC cracked at edge where screws were placed, close to the well point. Piece chipped off. Maybe the screws were caught on something and pressure from the screws bending cracked the PVC**
- **Used fishing line again to tighten down the sleeve.**

<u>January 6, 2015</u>

Well #7 – Exposed-Screen System B

NOTES – Slight alterations made

- **2nd prototype – schedule 40 PVC pipe was shorter, so had to PVC glue a 2nd pipe (sch20) to it**
- **Started sleeve immediately after the belled end. Used electrical tape and fishing line.**
- **Filed down the screws on the belled-end**
- **Cut notches right under the belled end and about 15cm away from the slots on the opposite end**
- **Check every 0.1m for distance between drive rod and PVC pipe (make sure well point did not separate from the pipe) and also to make sure the drive rod is not stuck at the bottom.**

4:28pm – Began coring

4:40pm – Hit root. Started new coring

4:46pm – took sample at 0.5m

4:52pm – took sample at 1.0m

4:55pm – took sample at 1.3m

5:11pm – Inserted Exposed-Screen System B and started hammering at 1.25m

5:14pm – Checked inner drive rod and distance between drive rod and PVC pipe at 1.45m. Everything okay.

5:16pm – Checked again at 1.65m. Everything okay.

5:17pm – Checked again at 1.85m. Everything okay.

5:19pm – Checked again at 2.0m. Everything okay.

5:20pm – Checked again at 2.1m. Everything okay.

5:23pm **-** Checked again at 2.25m. Everything okay. Stopped drilling and removed drive pipe easily. No issues.

*****Checked Depth to Water*** *– 8.95ft (top of pipe to water level) – 3.87ft (top of pipe to ground level) =5.08ft or 1.55meters.*

NOTES

- **1.25" PVC pipe removed successfully.**
- **Drilled (hammered) a total of 1.0m**
- **Screen moved up about ¼ meter**
- **Might try PVC gluing the sleeve (top & bottom of the sleeve) to the PVC pipe.**

- **Length of strokes for hammering was shorter than the previous drilling.**

January 7, 2015

Well #8 – Exposed-Screen System B

NOTES

- **Using Schedule 20 200psi pipe**
- **Filed down screws to make smooth**
- **Applied PVC glue to the screws and the gap in between the PVC and the well point to keep water and sand from entering through any holes and/or gaps. Also applied PVC glue in between the slots on the screen.**
- **PVC glued sleeve (top and bottom) to the PVC pipe. Made sure that the sleeve started immediately after the belled end**
- **Cut notches in the PVC pipe for the fishing line**
- **Applied fishing line (after PVC gluing) to hold the sleeve down and electrical tape to hold everything in place**
- **Will make small strokes for hammering (raising hammer only 15cm)**
- **Will count strokes it takes for drilling**

8:53am – Began Coring

9:05am – Hit root and started coring again in different spot

9:15am – Sample taken at 0.5m

9:19am – Sample taken at 1.0m

9:25am – Sample taken at 1.25m and stopped coring

Prepped piping for drilling.

10:13am – Inserted PVC pipe into hole and started hammering at 1.15m using short strokes (raising about 15cm)

10:15am – Checked inner drive rod and distance between drive rod and PVC pipe at 1.40m. Everything okay. *50 strokes*

10:17am - Checked inner drive rod and distance between drive rod and PVC pipe at 1.60m. Everything okay. *50 strokes*

10:20am - Checked inner drive rod and distance between drive rod and PVC pipe at 1.75m. Everything okay. *110 strokes*

10:24am - Checked inner drive rod and distance between drive rod and PVC pipe at 1.90m. Everything okay. *100 strokes*

10:28am - Checked inner drive rod and distance between drive rod and PVC pipe at 2.05m. Everything okay. *175 strokes.* Stopped Drilling.

*****Checked Depth to Water** – 9.5ft (top of pipe to water level) – 3.28ft (top of pipe to ground level) =6.22ft or 1.90meters.*

NOTES

- **Removed drive pipe and PVC pipe successfully**
- **Drilled (hammered) a total of 0.9m**
- **Sleeve for screen remained in same location as it was placed before drilling. Using the PVC glue could be the key. Need to confirm with more drilling tests.**
- **Total of 485 strokes for hammering**

NOTE – REMOVED WELL#5 FROM THE GROUND. USED 4" PVC PIPE AND AUGER AND FINALLY DR. MACCARTHY FIT 1.5" BELLED END OVER THE WELL POINT AND <u>PULLED IT OUT OF CLAY</u>.

Well #9 – Exposed-Screen System B

Notes – Tried to mimic process for well#8

- **Using Schedule 20 200psi pipe**
- **Filed down screws to make smooth**
- **Applied PVC glue to the screws and the gap in between the PVC and the well point to keep water and sand from entering through any holes and/or gaps.**
- **PVC glued sleeve (top and bottom) to the PVC pipe. Made sure that the sleeve started immediately after the belled end. This time DID NOT apply PVC glue in between the slots on the screen.**
- **Cut notches in the PVC pipe for the fishing line**
- **Applied fishing line (after PVC gluing) to hold the sleeve down and electrical tape to hold everything in place**
- **Will make small strokes for hammering (raising hammer only 15cm)**
- **Will count strokes it takes for drilling**

11:48am – Began coring

11:56am – Hit root. Restarted coring

12:07pm – Took sample at 0.5m

12:11pm – Took sample at 1.0m

12:16pm – Took sample at 1.45m. Stopped coring.

Took a break to remove other well point from the ground from last trip.

1:46pm – Began hammering at 1.25m

1:48pm - Checked inner drive rod and distance between drive rod and PVC pipe at 1.75m. Everything okay. *100 strokes*

1:53pm - Checked inner drive rod and distance between drive rod and PVC pipe at 1.95m. Everything okay. *100 strokes*

1:55pm - Checked inner drive rod and distance between drive rod and PVC pipe at 2.09m. Everything okay. *100 strokes*

1:58pm - Checked inner drive rod and distance between drive rod and PVC pipe at 2.15m. Everything okay. *100 strokes*

2:02pm - Checked inner drive rod and distance between drive rod and PVC pipe at 2.27m. Everything okay. *125 strokes*

*****Checked Depth to Water*** *– 9.25ft (top of pipe to water level) – 4.25ft (top of pipe to ground level) =5.00ft or 1.52meters.*

Notes

- **When trying to pull the drive rod out of the PVC pipe, there was a brief moment of difficulty. It was probably sand.**
- **Removed PVC pipe with success! Needed to leverage the pipe in order to get it out of the ground. This is possibly due to clay being in the ground at around 2 meters.**
- **Screen sleeve stayed in tact. PVC glue could be the reason!**
- **Total of 525 total strokes**

Appendix H. Data Collection of Wells Drilled in Madagascar

Table 6. Data Collection of Wells Drilled in Madagascar

Data Collection Sheet	Tamatave, Madagascar	
Forage/puits (#) - Drilling/Well (#)	**#1**	**#2**
Jour, Mois, Annee Date	**2/4/2015**	**2/5/2015**
L'heure exacte au debut de craissage de trou pour le forage Start coring time	**16H 17mn**	**15h 36mn**
L'heure exacte a la fin de craissage de trou pour le forage End coring time	**16h 30mn**	**16h 00mn**
Profondeur de trou de forage, avant de installer le tuyau PVC (en metre) Borehole depth, before installing PVC pipe (meters)	4,60m	4,20m
L'heure exacte au debut de "tappage" de forage dans le trou Start Time of Hammering	**16h 32mn**	**16h 05mn**
L'heure exacte a la fin de "tappage" de forage End Time of Hammering	**16h 58mn**	**16h 44mn**
Nombre total de "tappes" avec le marteaux, sur le tuyau galva Total # of hammer strikes on the galvinized pipe	263	302
Distance maximum (moyen) entre le marteau et tuyaux galva (cm) **(c'est a dire - quel distance on monte le marteau, avant de tapper sur le tuyaux galva)** Maximum average distance the hammer is lifted before striking the galvanized pipe (cm)	70cm	70cm
Profondeur qu'on a installe le forage dans le nappe (m) Depth that the pipe was cored into the ground (m)	3,10m	3,80m
Depth that the pipe was hammered into the ground (m)	1,50m	0.6m
Profondeur total du forage (m) Total drilling depth	4,60m	4,40m
Type et couleur de terre pendant le craissage? (Example: sable, noir)		
Type and color of earth during drilling ? (Example: sand, black)		
1m	**blanc,jaune**	**noir**
	white, yellow	black
2m	**blanc fine,gris**	**marron,**
	fine white, gray	brown
3m	**gros sable:jaune**	**jaune claire,noir**
	coarse sand, yellow	light yellow, black
4m	**noir**	**gris**
	black	gray
Succes? (Probleme avec materiaux ou outil(s)?) (OUI ou NON. Si OUI, explique...)	**oui**	**oui**
	yes	yes
List any and all ptoblems below. Please make sure to label with which well the issue occurred. **Notes:**		
Le problème avec le tutaux PVC car c'est fragile et difficille de taper avec le marteau,c'est pourquoi il reste 1,40m en haut le tuyaux PVC. LE problème de la deuxième tuyaux c'est la meme de la première,il reste 1,60m en haut le tuyaux pvc		
There was a problem with the PVC pipe. It is fragile and difficult to hit with the hammer, which is why there is 1.4 m of PVC pipe still above the ground. The second pipe has the same problem as the first pipe, and it is 1.6m out of the ground.		

Appendix I. Complete Cost Breakdown of Each Well

Table 7. Cost of Well #1 – Cased System

Well #1 - Cased System						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
1" PVC Adapter	Sch 40 Adapter	$0.93	1	pieces		$0.93
1" Rigid Drive Couplings		$2.80	1	pieces		$2.80
1.5" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$3.61	15	ft	$2.71	$2.71
1.5" Rigid Drive Couplings	Included with purchase of Rigid Conduit Pipe	$0.00	3	pieces	$0.00	$0.00
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	pieces		$9.05
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces		$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 20 200 psi PVC Pipe	1" PVC Pipe - 10 ft lengths - Total 10 ft	$1.68	1	ft		$1.68
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	1	ft		$0.00
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$19.24**

Table 8. Cost of Well #2 – Exposed-Screen System A

Well #2 - Exposed-Screen System A						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	piece		$9.05
1.25" PVC Adapter	Sch 40 Adapter	$1.13	1	piece		$1.13
1.25" Rigid Drive Couplings		$3.50	1	piece		$3.50
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 20 200 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths	$0.27	10	ft		$2.70
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$20.12**

Table 9. Cost of Well #3 – Exposed-Screen System A

Well #3 - Exposed-Screen System A						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	piece		$9.05
1.25" PVC Adapter	Sch 40 Adapter	$1.13	1	piece		$1.13
1.25" Rigid Drive Couplings		$3.50	1	piece		$3.50
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 20 200 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths	$0.27	10	ft		$2.70
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$20.12**

Table 10. Cost of Well #4 – Exposed-Screen System A

Well #4 - Exposed-Screen System A						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	piece		$9.05
1.25" PVC Adapter	Sch 40 Adapter	$1.13	1	piece		$1.13
1.25" Rigid Drive Couplings		$3.50	1	piece		$3.50
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 20 200 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths	$0.27	10	ft		$2.70
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$20.12**

Table 11. Cost of Well #5 – Exposed-Screen System A

Well #5 - Exposed-Screen System A						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	piece		$9.05
1.25" PVC Adapter	Sch 40 Adapter	$1.13	1	piece		$1.13
1.25" Rigid Drive Couplings		$3.50	1	piece		$3.50
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 40 370 psi PVC Pipe	1.25" PVC Pipe - 10 ft lengths	$0.55	10	ft		$5.51
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$22.93**

Table 12. Cost of Well #6 – Exposed-Screen System B

Well #6 - Exposed-Screen System B						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	pieces		$9.05
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 40 370 psi PVC Pipe	1.25" PVC Pipe - 10 ft lengths	$0.55	10	ft		$5.51
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Pan Head Screws	100 pieces per box	$0.05	4	pieces		$0.20
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$18.51**

Table 13. Cost of Well #7 – Exposed-Screen System B

Well #7 - Exposed-Screen System B						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	pieces		$9.05
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 40 370 psi PVC Pipe	1.25" PVC Pipe - 10 ft lengths	$0.55	10	ft		$5.51
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Pan Head Screws	100 pieces per box	$0.05	4	pieces		$0.20
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$18.51**

Table 14. Cost of Well #8 – Exposed-Screen System B

Well #8 - Exposed-Screen System B						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	pieces		$9.05
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 20 200 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths	$0.27	10	ft		$2.70
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Pan Head Screws	100 pieces per box	$0.05	4	pieces		$0.20
PVC Cement	Fee based on 20 total uses	$4.87			$0.24	$0.24
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$15.94**

Table 15. Cost of Well #9 – Exposed-Screen System B

Well #9 - Exposed-Screen System B						
Tools & Materials	**Notes**	**Original Cost per Piece/ft**	**# of Pieces/ft**		**Drilling Equipment Fee (fee based on use per well)**	**Total Cost**
2.5" Expendable Drive Point	Steel Point with O-ring - Product Number: DP212S	$9.05	1	pieces		$9.05
3/4" Rigid Conduit Pipe	10 ft lengths - Fee based on 20 total uses	$1.83	15	ft	$1.37	$1.37
3/4" Rigid Drive Couplings	Fee based on 20 total uses	$1.96	3	pieces	$0.29	$0.29
Aluminum Drive Caps	Donated by the Machine Shop	$0.00	1	pieces	$0.00	$0.00
Breathable Polyester Sleeve	Borrowed from USF	$0.00	2.5	ft		$0.00
Plumbers Tape	Fee based on 3 total uses	$4.27			$1.42	$1.42
Schedule 20 200 psi PVC Pipe	1.25" PVC Pipe - 20 ft lengths	$0.27	10	ft		$2.70
Schedule 40 370 psi PVC Pipe	1.5" PVC Pipe - 10 ft length -For Coring - Borrowed from USF	$0.00	10	ft		$0.00
Pan Head Screws	100 pieces per box	$0.05	4	pieces		$0.20
PVC Cement	Fee based on 20 total uses	$4.87			$0.24	$0.24
Electrical Tape	Fee based on 3 total uses	$1.97			$0.66	$0.66
Fishing Line	From Mercer University	$0.00			$0.00	$0.00
Total						**$15.94**

Appendix J. Cost of Materials for Madagascar Exposed-Screen System

Table 16. Cost of Materials for Madagascar Exposed-Screen System

Cost of Materials per Well for the Madagascar Exposed-Screen System					
Tools & Materials	**Notes**	**Cost per Piece (tube)**	**Estimated Number of uses for equipment/ materials**	**Drilling Equipment Fee based on uses per well**	**Total Cost**
Pressure PVC Pipe	6 m lengths - Pressurize Pipe- 28mm x 32mm	28,800.00	1.0	28,800.00	28,800.00
Galvinized Iron Pipe	6 m lengths - 15mm x 21mm	22,000.00	20.0	1,100.00	1,100.00
Galvanized Iron Point	GI pipe forged into a point by a local blacksmith	1,000.00	1.0	1,000.00	1,000.00
Galvanized Iron Coring Tool	6m - 15x21mm drive pipe welded to 0.1m - 26x24mm pipe	30,000.00	20.0	1,500.00	1,500.00
Breathable Sleeve	100% Polyester - 1 m	4,000.00	1.0	4,000.00	4,000.00
Electric Tape	20m roll	900.00	2.0	450.00	450.00
Fishing Line	25m roll	3,000.00	2.0	1,500.00	1,500.00
PVC Cement	15cm tube	12,000.00	6.0	2,000.00	2,000.00
Total cost (Ariary)					**40,350.00**
Total cost ($)					**$13.93**

Appendix K. Cost of Materials for Current Drilling Method in Madagascar

Table 17. Cost of Materials for Current Drilling Method in Madagascar

Cost of Materials per Well for Current Drilling Method used in Madagascar					
Tools & Materials	**Notes**	**Original Cost per Piece**	**Estimated Number of uses for equipment/materials**	**Drilling Equipment Fee based on uses per well**	**Total Cost**
Galvanized Iron Coring Tool	6m - 15x21mm drive pipe welded to 0.1m - 26x24mm pipe	30,000.00	20.0	1,500.00	1,500.00
Galvinized Iron Pipe	6 m lengths - 26mm x 34mm	45,000.00	1	45,000.00	45,000.00
Galvanized Iron Point	GI pipe forged into a point by a local blacksmith	1,000.00	1	1,000.00	1,000.00
Brass Screen	200 cm^2 used per well	3,000.00	1	3,000.00	3,000.00
Solder Wire	To hold the wire mesh	5,000.00	5	1,000.00	1,000.00
Total Cost per Well (Ariary)					**51,500.00**
Total Cost per Well ($)					**$17.78**