IN-SITU FLUID INJECTIONS TO ACHIEVE BIO-STIMULATED CALCITE PRECIPITATION IN EXPANSIVE SOILS

by

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A thesis

submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Civil Engineering

Boise State University

December 2020

BOISE STATE UNIVERSITY GRADUATE COLLEGE

DEFENSE COMMITTEE AND FINAL READING APPROVALS

of the thesis submitted by

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Thesis Title:	In-Situ Fluid Injections to Achieve Bio-Stimulated Calcite Precipitation in Expansive Soils
Date of Final Oral Examination:	13 November 2020

The following individuals read and discussed the thesis submitted by student Anish Pathak, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

For my parents – Gyan Nath Pathak and Sushila Sapkota Pathak.

ACKNOWLEDGMENTS

First and foremost, I would like to express my sincerest gratitude to my advisor, Dr. Bhaskar Chittoori, for his lasting support and encouragement throughout my time at Boise State. His welcoming nature, kind appreciation, trust, and unparalleled guidance motivated me to overcome all manner of challenges and ultimately reach my goal.

I extend my gratitude to fellow students and friends from the SuRGE research group at Boise State who have supported me and shared good memories with me during my time here – Bruno Perez, Connor Asmus, Amit Gajurel, Touhidul Islam, Sikha Neupane, Austin Berry, Somaye Asghari.

Endless love and appreciation to my family members and friends from Nepal who have supported me and forever pushed me to achieve the best in life. I am grateful to my wife, Saidy, for helping me get through the most stressful of times. All of you people are jewels of my life and your unparalleled affection, excellent suggestion and unbreakable trust will keep me inspired to do my best in life.

ABSTRACT

Expansive soils undergo vast changes in volume when subject to change in water contents and cause damages to infrastructure across the world. Traditional methods of tackling the problem of expansive soils using cement or lime are environmentally unfriendly and expensive. Microbial Induced Calcite Precipitation (MICP) is a novel method which uses bacteria in the soil to precipitate $CaCO_3$ (calcite) and improve the engineering properties of soils. Various laboratory studies have shown that this method can be applied successfully to treat expansive soils, but the field application of the method have barely been studied.

To study the applicability of MICP in the field, a protocol was developed to perform in-situ injection of chemicals through a borehole. Tests were conducted at a field site in Marsing, Idaho. Multiple rounds of chemical injections were performed, and soil samples were monitored for calcite content and swelling potential changes. Results showed an increase in calcite precipitation and decrease in swelling potential of the soil with each round of chemical treatment.

An additional study was conducted using experimental and numerical modelling procedures to understand the influence distance of the chemical injections in the soil. Moisture change data was collected after an in-situ injection with water and an influence distance of the injection was established. The field data was used to verify a finite element model in ABAQUS. The model was then used to study the effects of pressure, hydraulic conductivity, and sorption characteristics of soil in influence distance. Results

suggest that, in soils with low permeabilities, such as in the case of expansive soils, a higher matric suction can result in greater influence distances over time. It was also seen that change in pressure of injection had minimal effect in influence distance. This suggests that it may be possible to implement MICP protocols in expansive soils by injecting solutions through boreholes at very low pressures and longer durations.

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CHAPTER ONE: INTRODUCTION AND BACKGROUND

The Expansive Soil Problem

In civil engineering, structures are constructed on and supported by different soil deposits. Some soil deposits (e.g., well-compacted gravels and sands) in their natural form are better suited for construction than others (e.g., high plastic clays). When unsuitable or problematic soils are encountered, they need to be either removed and replaced by better soils or modified in place using chemical or mechanical means before they can sustain the applied loads by the superstructure. One such type of problematic soil is expansive soil. Expansive soils are a typical type of clay soil that undergo significant changes in volume when subject to changes in moisture content. Such behavior can result in detrimental effects on lightly loaded structures such as pavements. These types of soils, which have remarkably high plasticity typically contain the clay mineral montmorillonite that exhibits high swelling with an increase in water content. Expansive soils are widespread and annually cause billions of dollars in damages to various infrastructures around the world (Jones Jr & Holtz, 1973).

Engineers have developed several soil stabilization methods to address swelling and shrinking problems in expansive soils. Soil stabilization is the process in which soil properties are modified to improve their engineering behavior and achieve desired properties such as strength, stiffness, and workability. A popular method used to stabilize expansive soils is chemical stabilization. There are a number of chemical stabilizers that have been used over the years including traditional stabilizers such as lime, Portland cement, fly ash, and nontraditional stabilizers such as ammonium chloride and sulfonated oils, along with byproduct stabilizers such as kiln dust. Use of chemical additives such as cement and lime to stabilize expansive soils has increased over the last few decades. The pozzolanic reaction of lime-stabilized clay, its strength gains, and applicability in the pavement industry have been discussed in literature (Little, 1999). The use of cement materials to alter the properties of highly plastic clay has been described in literature (Little et al., 2000). The combination of lime and granulated blast furnace slag (Obuzor et al., 2011) have also been used for clay stabilization. Moreover, other chemical agents, e.g., acids or alkalines (Carroll & Starkey, 1971) and electro-osmosis or potassium (O'Bannon et al., 1976) are available to stabilize expansive soils.

Use of chemical stabilizers has a negative impact on the environment due to: (1) greenhouse gases generated to produce these chemicals; and (2) negative impacts on plant growth that come from increasing pH levels in soils after the process of treatment. The production of cement and lime is a prime source of greenhouse gases. UNEP (2010) reported that one ton of cement and lime production could release 1 to 1.2 tons of CO2 into the environment, respectively. That report also concluded that around 7-8% of CO2 emissions result from only cement production each year. Furthermore, cement and lime raise the pH levels of soil, consequently affecting flora and fauna.

In addition to the environmental issues, the durability of cement or lime treatments is also a concern as pavement failures can occur even after the stabilization with chemical stabilizers – due to loss of the stabilizing agent over time. Loss of stabilizers may be because of the external factors such as water table fluctuation and rainfall infiltration. Moreover, lime and cement stabilization can be counterproductive in soils containing high sulphate, where the formation of ettringite due to the presence of calcium-based stabilizers, e.g. lime, Portland cement and fly ash, can cause swelling and distresses of infrastructures (Little & Petry, 1992).

In addition to chemical stabilization, researchers have investigated innovative alternative foundation techniques such as drilled and belled piers, granular pile-anchors (Phanikumar et al., 2004; Rao et al., 2007), and sand cushion technique for counteracting expansive soil problems. However, these methods can be very expensive - especially for constructing lightly loaded structures like pavements. Hence, it is necessary to identify an alternative stabilization method that is both environmentally friendly, and cheaper than existing solutions.

MICP Background

In recent years, use of the Microbial Induced Calcite Precipitation (MICP) technique to modify the engineering properties of expansive soil has gained attention as an affordable and green method of problematic soil improvement (Ivanov & Chu, 2008). Microbes represent an important role in filling voids in the soil by precipitating calcium carbonate, therefore increasing the shear strength, compressive strength and stiffness, as well as reducing the hydraulic conductivity (Burbank et al., 2012).

MICP can be processed in two ways:

1. Bio-stimulation, which depends on altering the environmental condition by stimulating the indigenous bacteria present in the soil to precipitate calcium carbonate, by introducing various nutrients into the soil.
2. Bio-augmentation, which involves the introduction of the desired microbes along with nutrients required to stimulate the microbes into the soil.

Bio-stimulation is usually preferred rather than bio-augmentation, as stimulating native microbes that are related to the environment is likely to be more stable than artificially introducing bacteria into a new environment, which usually causes death to the native bacteria (Burbank et al., 2013). In bio-stimulation, indigenous bacteria are stimulated with nutrient and carbon sources, and this leads to an increase in the number of microbes and calcite precipitation. On the other hand, introduction of exogenous bacteria is not always successful because of the complex communal relationship of microbes including competition and parasitism.

Recent research showed that indigenous bacteria could be stimulated to precipitate calcite and stabilize expansive soil; calcite precipitation can significantly change soil-engineering properties. It has been observed that a decrease in the percentage of swelling by around 30 % (Chittoori et al., 2018) can be achieved. Touhidul et al. (2020) conducted a laboratory study on eight different types of natural and artificial soils with varying clay content and found considerable increase in soil strengths and reduction in soil swelling using bio-stimulation. The same study also found that calcite precipitation increased with increasing clay content in soils and speculated that MICP is more effective in the case of soils containing higher clay content due to the presence of higher bacterial populations.

Although, a considerable number of laboratory studies have been conducted on the effectiveness of MICP to date, only a few field trials have been performed in which microbes have actively been used to either increase the strength and stiffness of soils by microbially induced carbonate precipitation or reduce the hydraulic conductivity through biofilm formation. Contractor Visser & Smit Hanab applied a MICP treatment using bioaugmentation for gravel stabilization to enable horizontal directional drilling for a gas pipeline in the Netherlands in 2010 (van Paassen, 2011a). The treatment involved an injection of bacterial suspension developed in laboratory and two additional injections of chemical reagents containing urea and calcium chloride. Successful field trials of bioclogging have also been reported in the Netherlands and Austria, with the objective of reducing leakage through water-retaining constructions (Blauw et al., 2009). In this application, bio-stimulation was used by injecting solutions through a screen of wells at the crest of a ‘leaking’ dike in the Danube River in Greifenstein (Blauw et al., 2009; Lambert et al., 2010). Most studies and field applications of MICP are based on soils that are granular or fractured and consequently have a higher range of hydraulic conductivities. Applications on fine grained soils that have lower hydraulic conductivities have yet to be studied by a broader community of researchers.

Pressurized Injections and Fluid Flow in Soils

A study on the injection process and movement of chemical solutions in the soil is necessary for the design and application of MICP in expansive soils. Treatment of expansive soils by pressurized injection into the soil through drill holes or pipes have been used in the past. Pressurized injection of lime to treat swelling soils was discussed by Thompson and Robnett (1976) based on field observations by various other researchers. Pressure injected lime slurry in the subgrade could be forced along fracture zones, cracks, fissures, bedding planes, root lines, coarse-textured seams in varved clays, seams and fractures affected by the pressure slurry injection process, or other passages in the soil mass. It was reported that injection spacings in the rage of 1 to 2 m and pressures in range of 350 to 1350 kPa have been used for treatments in pavement and railroad subgrades, with treatments resulting in varying success rates. It is evident that injection processes are available for treating clays and treatment can be successful in some cases despite their low hydraulic conductivities. A study on the influence distance of pressure injections in low hydraulic conductivity soils is therefore necessary for understanding the possibilities of MICP applications.

To understand the lateral influence distance of fluid injections in soils, an understanding of soil water characteristics and fluid flow through pores is important. The flow of fluids through soil is an incredibly complicated process. Much has been written about the theory of flow through porous media, but natural soils are heterogeneous and consist of haphazard arrangement of pore sizes and distribution – making it difficult to accurately apply such theories. The theories could still, however, be used to get order-of-magnitude data about the effects of changing controllable variables. A form of Darcy's law applicable to grout injections is available in the literature that provides a relationship between hydraulic head, discharge, hydraulic conductivity, radius of the injection device, and radius of liquid penetration. In a practical use of the relationship, often the radius of liquid penetration is predetermined as part of the injection design and hydraulic head and discharge parameters are checked for safety or economic concerns (Karol, 2003). Truex et al. (2011) used Darcy's equation combined with transient viscosity relationships to plot injection radius and pressure responses in grout injection as a function of time for varying flow rates and highlighted that grout penetration is limited by gelling time and hydraulic conductivity of the subsurface. It can be inferred from the general relationship provided by Darcy's law, that influence distance of fluid injection highly depends on pressure and hydraulic conductivity of the porous medium.

Darcy’s law was originally conceived for flow in saturated porous media. Chemical injection processes in semi-arid regions, especially at shallow subgrade depths, would most likely occur under unsaturated conditions. Darcy’s law has been applied to unsaturated flows with an additional provision that hydraulic conductivity applied as a function of matric suction (Hillel, 2008). Matric suction exists due to the physical affinity, between water and the matrix of the soil, which includes both the adsorption of water onto particle surfaces and the attraction of water into capillary pores due to surface tension. When a suction gradient exists in soil, water will be drawn from a zone where the matric suction is lower to where it is higher. The matric suction of the soil can be shown as a function of water content (or saturation) in a plot that is known as the soil-water characteristic curve (Tuller & Or, 2005). Fredlund and Xing (1994) have provided an equation for calculating the soil water characteristic curve that is based on assumption that the shape of the curve is related to the pore-size distribution of the soil. It has been reported that the equation provides a good fit for soils ranging from sands, silts, and clays (Leong & Rahardjo, 1997; Zhai & Rahardjo, 2012). It is necessary to define the soil water characteristic curve for a proper analysis and modelling of unsaturated flow in soils.

A major difference in the saturated and unsaturated flow through any porous media is hydraulic conductivity. The hydraulic conductivity in unsaturated conditions is dependent on the water content of the soil itself, and consequently the matric suction (Hillel, 2008). As soil saturation decreases, a sharp decline in the hydraulic conductivity occurs by up to several orders of magnitude. An equation was proposed by Fredlund, Xing, and Huang (1994) to predict the hydraulic conductivity function for unsaturated soils based on the soil water characteristic curve. It was reported that the equation provided an excellent fit between data and theory and was able to integrate hydraulic conductivities for soils from zero to maximum water contents. Incorporating a saturation (or suction) dependent relationship for hydraulic conductivity into Darcy’s law can model a steady-state unsaturated flow process. In practice however, chemical injections into the soil is a transient process (Karol, 2003).

Transient unsaturated flow is fundamentally different than saturated flow and steady-state unsaturated flow. During transient unsaturated flow, water enters pores that were previously occupied by another fluid. Typically this fluid is air; and it is usually assumed that the displacement of the resident air does not impede the advance of water into a pore (Ferré & Warrick, 2005). This underlying assumption is also used in the Richards equation, a special expression that describes the movement of water through an unsaturated porous medium (Ferré & Warrick, 2005; Hillel, 2008). The Richards equation combines the equation for mass conservation to that of Darcy’s law with added provision for saturation dependence of hydraulic conductivity. The equation is highly nonlinear because of the interdependence of parameters involved (namely, the dependence of both the water content and the hydraulic conductivity on the soil's matric potential) and cannot be solved analytically. Numerical methods are required to successfully model transient fluid flow in unsaturated soils.

Research Objectives and Tasks

The research hypothesis of this thesis is that pressurized chemical injections can be used in the field to achieve bio-stimulated calcite precipitation in fine grained soils. A pictorial representation of the research is shown in Figure 0.1. To validate the hypothesis of this research, several research objectives were considered and are listed here:

1. To study the feasibility of precipitating calcite (through MICP) in the field using pressurized chemical injections.
2. To understand the lateral influence distance of fluid injections in different soils and recommend a method of implementation for MICP.

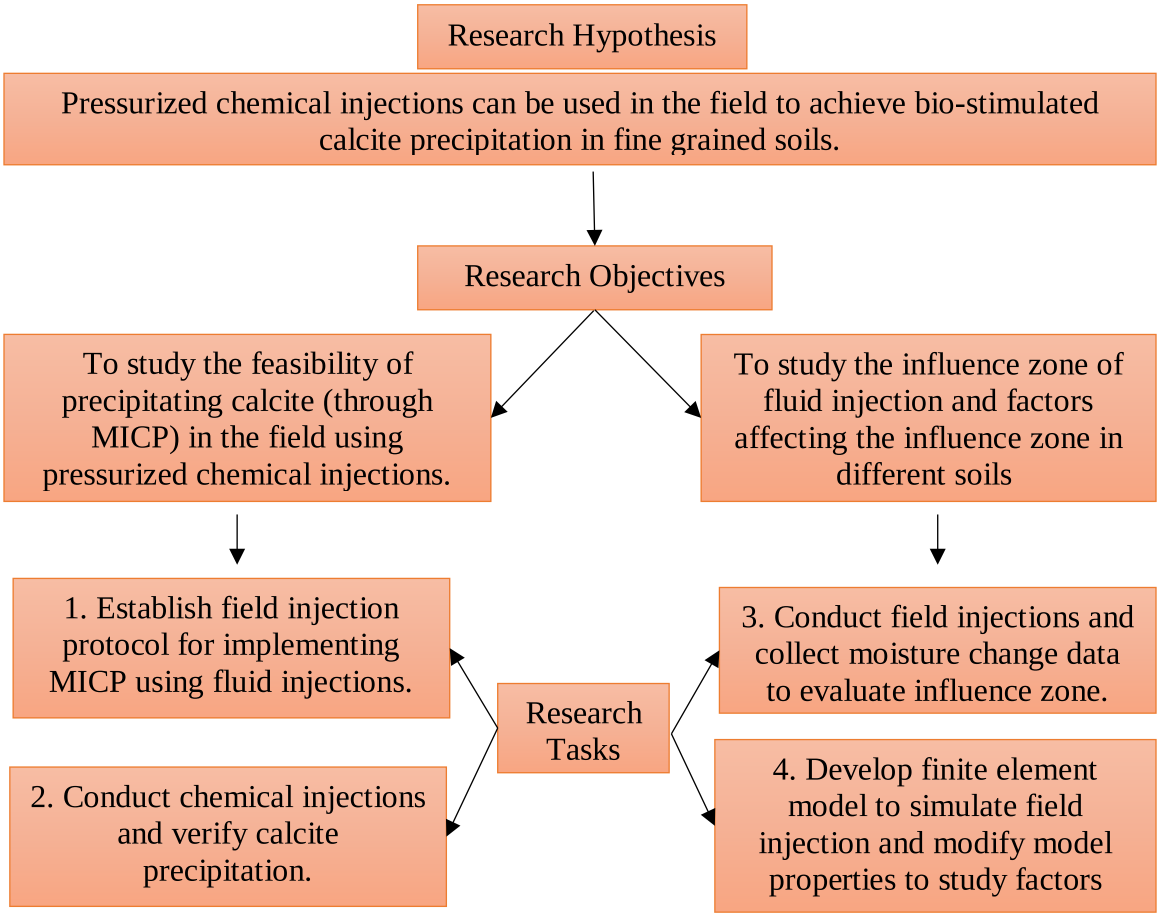


Figure 1.1. Pictorial representation of research work

The research tasks to accomplish these research objectives are given here:

1. An injection system using a pneumatic packer was developed and a field protocol for the implementation of MICP was established based on the laboratory protocols used by past researchers at Boise State University.
2. Bio-enrichment and bio-stimulation solutions were injected to induce precipitation of calcite in Marsing, Idaho. The calcite contents and swelling potential of the soil were monitored continuously through the injections to verify the changes in calcite and swelling index.
3. In-situ injection was performed at a field site in Marsing, ID and moisture content changes around the injection point was determined by taking soil samples at various depths and distances around the injection point to understand the influence zone.
4. Numerical modelling and simulations were carried out in ABAQUS software using the field injection results and effect of pressure, permeability, and sorption characteristics on influence zone of injection point was studied.

Organization of the Thesis

This thesis consists of an introduction in Chapter 1 and two manuscripts in Chapters 2 and 3 and a summary in Chapter 4. The manuscripts in Chapters 2 and 3 are inter-related. In the first manuscript, the feasibility of using a pressurized injection method for application of bio-stimulation to stabilize the expansive soils is studied. Manuscript one explains the effectiveness of the injection method as seen during the application of bio-stimulation in Marsing, Idaho. Increase in calcite precipitation and reduction of swelling potential after field injection are shown. The manuscript was published in the Geo-Congress 2020 conference (Geo-Institute of the American Society of Civil Engineers).

The second manuscript is a study on the injection method used in manuscript one and presents the results from field injections and numerical models that were aimed towards determining the lateral influence zone of injection. The manuscript presents results of a numerical simulation conducted to investigate the factors affecting the influence distance of field injections.

CHAPTER TWO: APPLICATION OF BIO-STIMULATED CALCITE PRECIPITATION TO STABILIZE EXPANSIVE SOILS - FIELD TRIALS

Abstract

This paper presents the results of a field implementation of microbial induced calcite precipitation to stabilize expansive soils in Marsing, Idaho. The field test was done by drilling 2.5” (6.35 cm) diameter holes at a spacing of 16” to 30” (40.6 cm to 76.2 cm) into the ground and, injecting bio-enrichment followed by bio-cementation solutions to stimulate the native bacteria and subsequently achieve calcite precipitation. The pH level of the soil, the calcite content and free swelling potential were monitored over time by collecting periodic soil samples from the injection points. An increase in pH from 8.3 to 9.7 was seen in the first seven days after the injection of the bio-enrichment solution. The calcite content in the soil increased and the free swelling potential decreased consistently with each subsequent injection of bio-cementation solution. The calcite content increased from 3% to 8% and the free swell index dropped from 114% to 29%. The results show that microbial induced calcite precipitation can be successfully replicated in the field for the stabilization of expansive soils.

Introduction

Expansive soils undergo significant changes in volume with changing water content. These soils are widespread and annually cause billions of dollars in damages to various infrastructures around the world (Jones Jr & Holtz, 1973). Various ground improvement techniques like chemical stabilization using lime or cement, deep soil mixing, and moisture barriers are employed to counteract problems due to these soils. However, engineers have observed subgrade failure even after lime and cement stabilization, attributed to: (a) stabilizer loss over time, or (b) certain physicochemical soil properties that render the stabilizer ineffective (other soils with similar index properties may respond well to the same stabilizer). Further, these chemical stabilizers have an adverse effect on the environment and economy. UNEP (2010) concluded that annually, around 7-8% of overall CO_2 emissions result from cement production alone. It is evident that there is a distinct need to develop sustainable and eco-friendly solutions to mitigate the problems with expansive soils.

Researchers have investigated innovative alternative foundation techniques such as drilled and belled piers, granular pile-anchors (Phanikumar et al., 2004; Rao et al., 2007), and sand cushion technique for counteracting expansive soil problems. However, these methods can be very expensive - especially for constructing lightly loaded structures like pavements. Hence, it is important to identify both environmentally friendly and cost-effective methods. Using indigenous bacteria to stabilize expansive soils falls into this category.

Bacteria are a dominant soil inhabitant with ~10^6-10^{12} bacterial cells per gram of soil and containing as many as 10^4 different genotypes (Torsvik et al., 1990). Microbial metabolic activities often contribute to selective cementation by producing relatively insoluble organic and inorganic compounds both within and outside the cellular structure (Stocks-Fischer et al., 1999). Microbial Induced Calcite Precipitation (MICP) is one such technique where the metabolic activity of certain types of bacteria present in the soil (*Sporosarcina pasteurii*) results in the formation of inorganic compounds (such as

$CaCO_3$) outside the cellular structure; these compounds can bind soil particles together. In MICP, one mole of urea, $(NH_2)_2CO$, is hydrolyzed into two moles of NH_4^+ and one mole of CO_3^{2-} by the microbial enzyme urease: $CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}$. In the presence of calcium ions, CO_3^{2-} spontaneously precipitates as calcium carbonate: $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$. NH_4^+ generation increases local pH (~9.5), and importantly further increases the rate of calcium carbonate precipitation. Researchers have demonstrated the MICP method by combining the ureolytic bacterium, *Sporosarcina pasteurii* (bio-augmentation), urea, and a source of calcium ions in laboratory and in the field (van Paassen, 2011b; van Paassen et al., 2010; Whiffin et al., 2007). Burbank et al. (2013) demonstrated that biomineralized soils showed properties indicating that calcite precipitation increased soil resistance to seismic-induced liquefaction.

Researchers have shown that MICP was able to mitigate seismic-induced liquefaction, reduce permeability and compressibility, and increase shear strength (Burbank et al., 2011; DeJong et al., 2006; Martinez et al., 2013; Qabany & Soga, 2013; Van Paassen, 2009; Whiffin et al., 2007). There are two application strategies for this technology: *bioaugmentation* and *biostimulation*. *Bioaugmentation* is a process where urease-producing exogenous bacteria are added to the soil, whereas *biostimulation* uses indigenous bacteria already present in the soil to precipitate calcite.

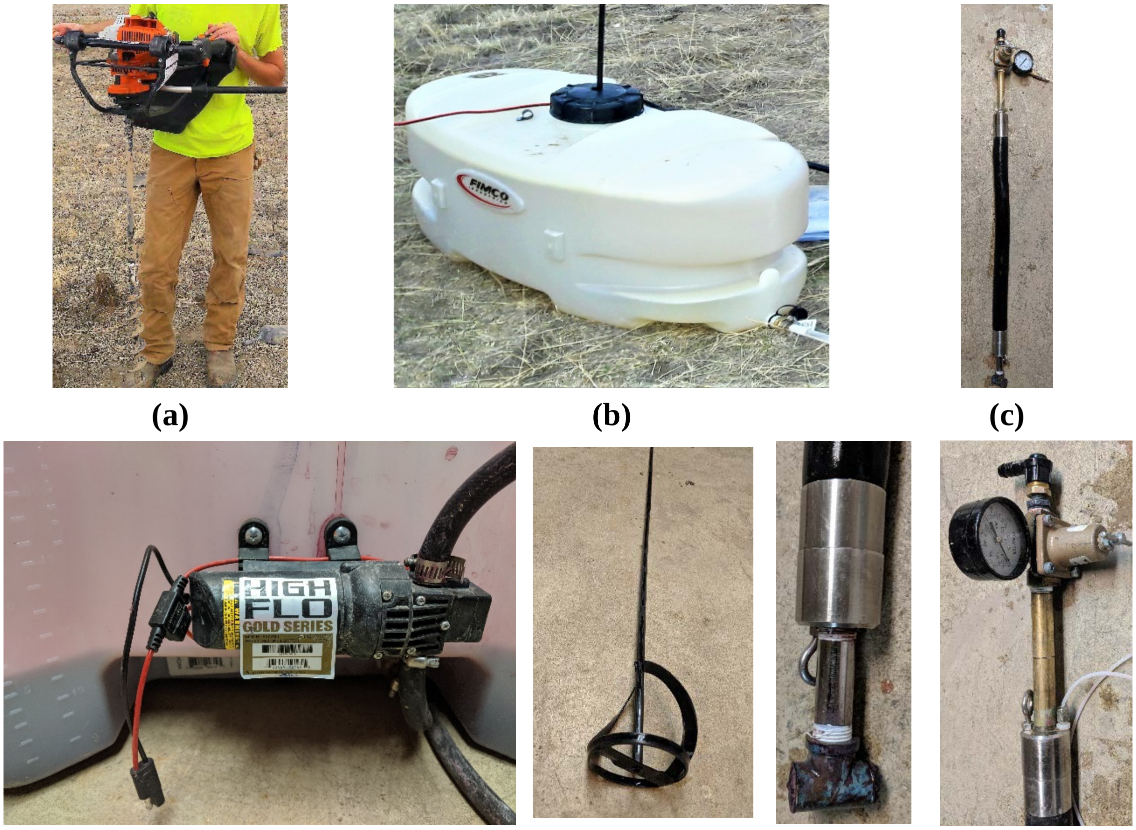
Burbank et al. (2013) demonstrated that it was possible to stimulate indigenous microorganisms (bio-stimulation) to precipitate calcite. This method can be applied in situ without the need for reconstruction which involve excavation and mixing. This solution meets or lowers the costs of expansive soil stabilization and can be easily applied to soil with existing construction equipment used for treating expansive soils. By simply injecting the treatment solutions to the required depth we will avoid costly reconstruction using chemically stabilized subgrades or other design alternatives used to stabilize expansive soils.

This paper covers the results of an attempt to improve the behavior of expansive soils using MICP in the field. The field test was carried out along US-95 in Marsing, Idaho - 45 miles west of Boise, Idaho. The soil from the test location was classified as CH (High Plastic Clay) according to the Unified Soil Classification System (USCS). An Atterberg limit test on the soil showed a liquid limit of 111 and plasticity index of 71, while the natural moisture content ranged between 36 to 38 percent.

The field implementation method carried out in this study involves pressurized injection of a bio-enrichment solution and a bio-cementation solution into the ground at various time intervals to induce calcite precipitation. The injections were made in 2.5” (6.35 cm) diameter holes drilled up to a depth of 30” (76.2 cm). Bio-enrichment solution, consisting of urea, sodium acetate anhydrous and solulys, was injected to stimulate the growth of bacteria in the soil. Subsequently, multiple bio-cementation solutions were injected at various intervals to facilitate the precipitation of calcite. Soil samples taken from injection points were tested after each round of injection and the change in calcite content was observed.

Equipment Setup

The equipment used in the field test included – a handheld power auger (to drill borehole), Pneumatic packer system (to seal the borehole), water tank or reservoir (to hold treatment solutions), hydraulic pump (to inject treatment solutions under pressure), and soil core (to collect samples from different depths). A portable gas-powered earth auger was used to drill injection points in the field site (Figure 0.1-a). A spiral auger head 2.5” (6.35 cm) in diameter was used to drill holes up to a depth of 30” (76.2 cm) into the ground. A 25-gallon (94.6 liters) solution tank (Figure 0.1-b) was connected to a portable water pump (Figure 0.1-d) to feed the injection solution. The water pump could be operated in the field by connecting it to a 12V car battery. The water pump had a rated capacity to pump 5.5 gallons (20.8 liters) per minute (20 liters per minute) at a pressure of 60 psi (413.7 kPa). A paddle mixer was used to mix the solutions in the tank (Figure 0.1-e). The outlet from the portable water pump was connected to a pneumatic packer that injected the solution into the ground (Figure 0.1-c). A single point pneumatic packer was used for this project. The packer can be inflated with air through a 1/8” (3.2 mm) outer diameter tubing that extends from the packer to the ground surface. A manual hand pump with a gauge can be used to inflate the packer. The outer diameter of the packer used for this project was 1.8” (4.6 cm) when uninflated. On the surface, the inlet of the packer (Figure 0.1-c. i) is connected to the outlet from the water pump. At the outlet of the packer (Figure 0.1-c. ii), a PVC Tee connection was attached such that the solution would be pushed out laterally from the tube. A pressure gauge at the inlet of the packer was used to read the pressure within the injection tube.



(a) **(b)** **(c)**

(d) **(e)** **(c. i)** **(c. ii)**

Figure 2.1. Photographs of equipment (a) Handheld power auger (b) 25-gallon Tote tank (c) Pneumatic packer (c.1) Packer outlet (c.2) Packer inlet (d) Water pump (e) Paddle mixer

Injection Method

The chemicals were injected into the ground through seven injection points that were spread apart at fixed distances to form two interlocking grids. The first grid consisted of four holes spaced 16” (40.6 cm) on center and the second grid consisted of four holes spaced at 30” x 20” (76.2 cm x 50.8 cm) (see Figure 0.2). The injected solutions consisted of two separate mixes for enrichment and cementation shown in Table 0.1. The chemicals were purchased in powder form and mixed on site in the tote tank (reservoir) using a paddle mixer. The tank was thoroughly cleaned between injections to ensure no calcite buildup inside the tank.

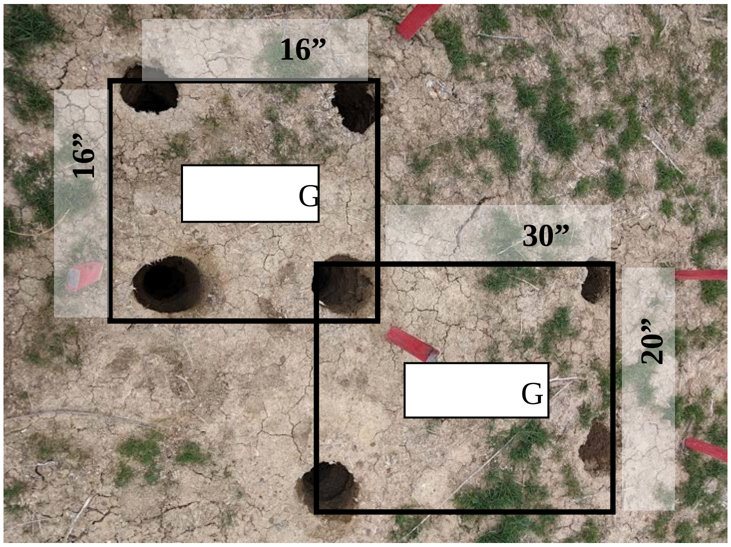


Figure 2.2. Layout of Injection Points

Injection

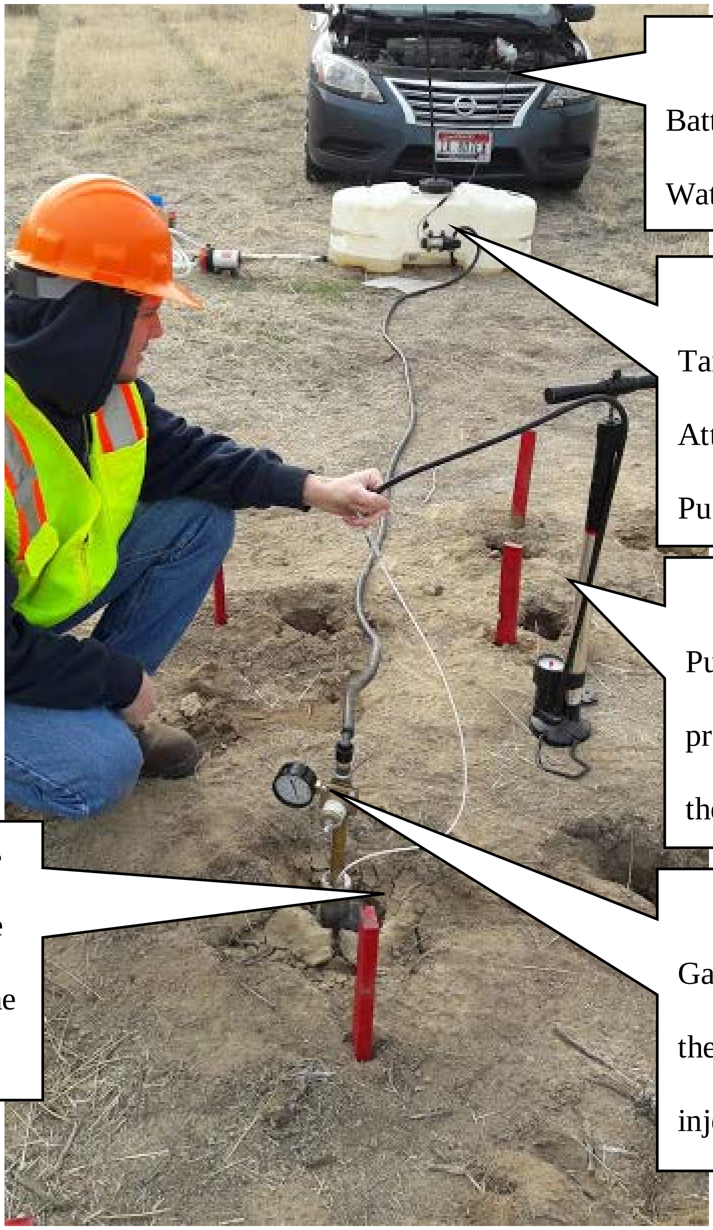
The pneumatic packer tube was inserted into the injection points to inject solutions into the ground. A hand pump was used to inflate the rubber lining on the packer tube and seal the holes. This prevented the solutions from easily raising back to the surface. Figure 0.3 shows the entire equipment setup used for injection of solutions in the field.

The injections were done at pressures ranging between 14 psi (96 kPa) to 20 psi (138 kPa). Where fracking of the soil is a concern at high pressures like these, the pressure gauge did not show a loss of pressure after reaching a peak point, which is a common observation when fracking occurs. This suggests that fracking did not occur, and the injection was not going through preferential pathways during the operation.

Table 2.1. Concentration of Chemicals Used in Enrichment and Cementation Solutions

S.N.	Chemicals	Concentration (gm/ltr)	
		Enrichment Solution	Cementation Solution
1	Urea	20	20
2	Sodium Acetate Anhydrous	8.2	4.1
3	Solulys	0.5	0.5
4	Calcium Chloride	-	27.74

Each injection point was injected with 3-6 gallons (11.35 - 22.7 liters) of solution. Injection operation was stopped when the treatment solutions started rising from the sides of the packer lining on to the surface. As the injection process continued, soil surrounding the packer deformed, leaving a gap between the packer lining and the soil through which treatment solutions could escape upwards. The research team was able to inject about 4 gallons (15 liters) of solution per point during each round of injection. The amount of treatment solutions required for each cycle was determined based on the pore volume of the targeted treatment section. The research team targeted to treat approximately 2 ft (60.96 cm) of soil across each grid. The approximate pore volume of the target area (16" X 16" X 24" or 40.64 cm x 40.64 cm x 60.96 cm) was determined to be 19 gallons (71.92 liters). To ensure that all pores had access to the treatment solutions 24 gallons (90.84 liters) of the treatment solutions were injected for each round of treatment.



12 V Car Battery Powers the Water Pump

Solution Tank and Attached Water Pump Feed the

Hand Pump used to pressure inflate the rubber lining

Solution is injected below the surface through the packer tube

Pressure Gauge attached to the packer reads injection pressure

Figure 2.3. Equipment Setup for Injection of Solution in Field

The enrichment and cementation solutions were injected at different time intervals depending on soil pH. The first injection was done with the enrichment solution. The consecutive injection of cementation solution was done after 7 days when the pH of the soil had risen from 8.3 to 9.7 (see Figure 0.4 below). This is likely due to a rise in population of the urease producing bacteria that facilitate in calcite precipitation. After the injection of enrichment solution, three consecutive injections of cementation solutions were made at an interval of 7 days. A fourth injection of cementation solution was done 14 days after the third cementation. The timeline for all injections made during the study period is: Day 0 – Enrichment, Day 7 – Cementation Round 1, Day 14 – Cementation Round 2, Day 21 – Cementation Round 3 and Day 35 – Cementation Round 4.

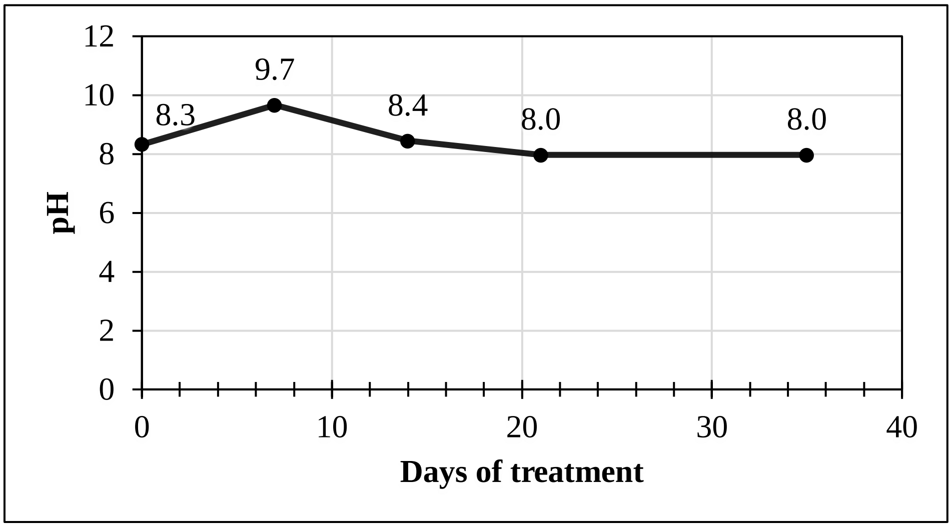


Figure 2.4. Change in soil pH with time since first injection

Observation and Results

<u>Lateral Influence of Injection</u>

During the process of injection, the solution was seen to be flowing into a neighboring injection point through the soil. This observation was made within injection points at 16” (40.6 cm). This suggests that the solutions could flow laterally up to at least the distance of 16” (40.6 cm) when injected at a pressure of 20 psi (138 kPa). The following picture shows the leakage of solution from one injection point to another (Figure 0.5).

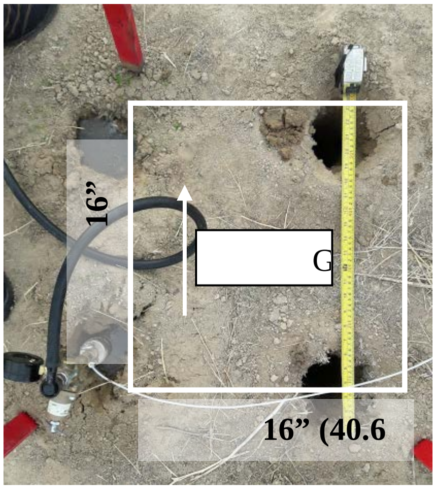


Figure 2.5. Flow of solution between injection points

The flow of solution into neighboring injection points was seen between point 3 and point 4 during the injection of the enrichment solution and first round of cementation solution. However, during the second round of cementation injections, it was observed that the injection was flowing between point 1 and point 3. The change in flow path could be due to blockage of flow lines with gradual precipitation of calcite in the soil. As calcite precipitation occurs and particles are bonded together, the initial flow path can get restricted. So, a consecutive injection in the same point could result in the solution taking alternate pathways.

Calcite Concentration

The calcium carbonate content in the soil was detected by mixing the air-dried soil with 1N HCL in an airtight container and measuring the pressure of carbon dioxide gas produced. A calibration of pressure readings with known amounts of calcium carbonate can be used to calculate the calcium carbonate in the soil sample. Soil samples from the field showed that there was consistent rise in concentration of calcite at the injection points with every round of cementation injection as seen in Figure 0.6.

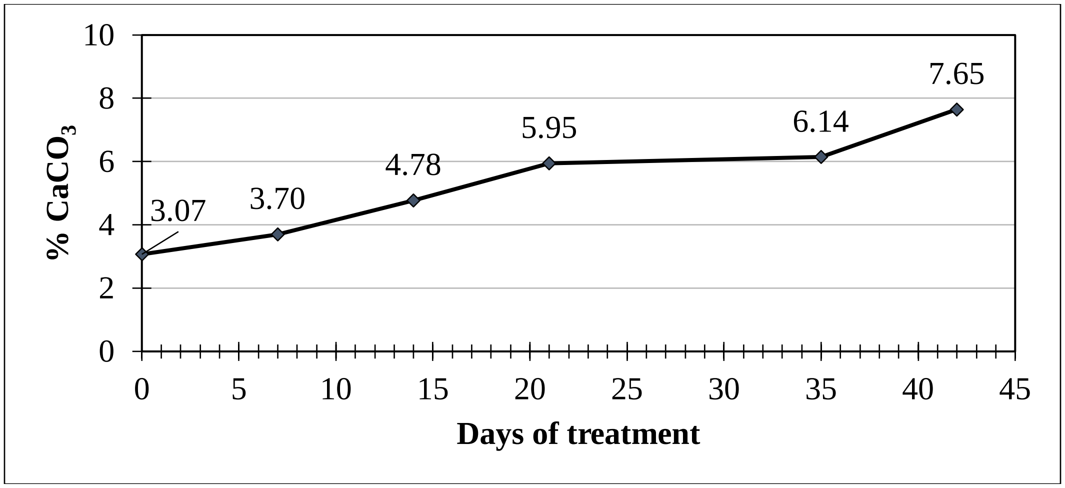


Figure 2.6. Change in calcite content

Swelling Potential

The swelling potential of the soil was compared using a free swell index test with kerosene. The free swell index test is an experimental procedure performed to estimate the expansion potential of a given soil (Holtz & Gibbs, 1956). It is defined as the ratio between the difference in volumes of a soil submerged in distilled water (polar fluid) and kerosene (nonpolar fluid) without any external constraints for 24 hours to the volume of the soil submerged in kerosene after 24 hours.

In this test, two representative oven-dried soil samples (passing # 40 sieve) weighing 10 grams each were poured into two graduated cylinders of 100 ml capacity. One cylinder was filled with distilled water while the other was filled with kerosene up to the 100 ml mark. Entrapped air was removed by minor shaking and stirring with a glass rod. Soil samples are allowed to attain equilibrium state (without any further change in the volume) for a duration of 24 hours (Sridharan & Prakash, 2000). The final volume of soil samples in both cylinders are recorded after 24 hours, and the FSI is measured using equation 1.

$$Free\ Swell\ Index\ (FSI)\ (\%) = \frac{(V_d\ - V_k\ )}{V_k} \times 100 \tag{1}$$

Where,

V_d = Volume of the soil sample from the graduated cylinder containing distilled water.

V_k = Volume of the soil sample from the graduated cylinder containing kerosene.

The swelling potential of the soil was compared using a free swell index test with kerosene. Tests with samples collected at injection points showed that the free swell index decreased significantly with each treatment at the injection points (Figure 0.7).

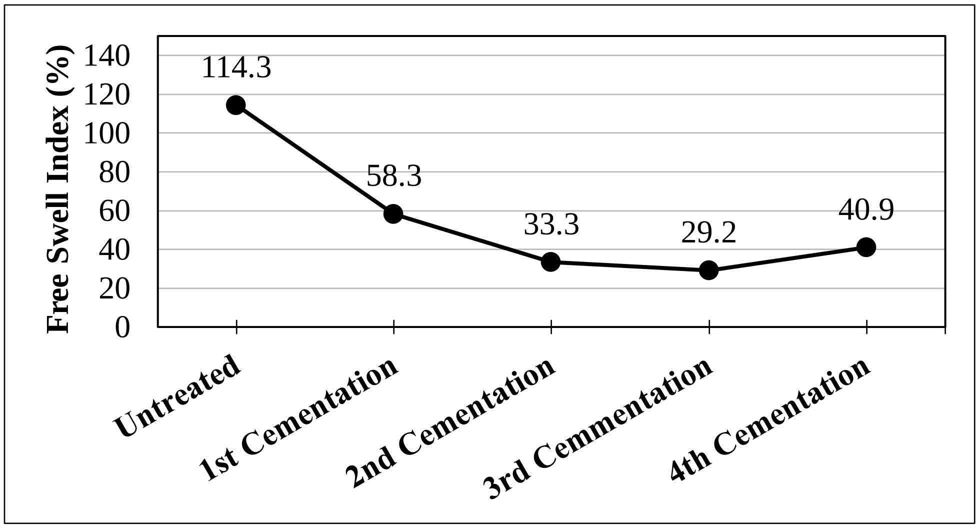


Figure 2.7. Change in free swell index with treatment injections

Conclusion and Recommendation

The results of the field test showed that the calcite content increases significantly with each successive injection of cementation solution and reduces swelling potential of the soil. Calcite precipitation increased with treatments (up to 8% total) and the free swell index dropped from 114% to 29%. This study shows that microbial induced calcite precipitation can be successfully replicated in the field through successive injections of enrichment and cementation solutions into the soil. The current method of injection and treatment could be applied in existing highways that are built on expansive soils. This could potentially reduce the repair and maintenance costs in the long term.

The treatment methods still need perfection and further research is necessary to optimize the process. The homogeneity of the calcite precipitation and its effects on the volumetric behavior of expansive soils need to be studied in a larger scale to understand the full benefits of MICP. The durability of the treatments and calcite precipitate also need to be studied. Instrumentation and on-site measuring devices will be necessary to measure and monitor the physical and chemical changes in the soil. An in-depth study in the possibility of field application could potentially lead to a revolutionary method for stabilizing expansive soils.

CHAPTER THREE: STUDYING THE INFLUENCE DISTANCE OF SUBSURFACE FLUID INJECTIONS IN LOW-HYDRAULIC-CONDUCTIVITY SOILS TO ENABLE THE APPLICATION OF MICROBIAL INDUCED CALCITE PRECIPITATION

Abstract

The prospect of Microbial Induced Calcite Precipitation (MICP) for improving soil behavior has been a topic under investigation for over a decade now. Recent studies have expanded its application to clayey soils. However, in the case of clayey soils gravity feeding the treatment solutions to achieve MICP is not an option due to their low permeability. Hence, pressurized fluid injections were proposed as a possible application method. Current injection methods use pressures higher than 650 kPa to allow fluid movement, especially in clays. These high pressures could be counterproductive when treating shallow depths for lightly loaded structures such as pavements. Under lower pressures the influence zone of each injection location would be dependent on soil properties such as permeability, density, and soil suction. However, current understanding of the effect of these parameters on the influence zones is very limited. Hence, experimental, and numerical modeling studies were conducted to expand this understanding and the results of these studies are presented in this paper. In-situ injections were performed in a clayey soil through a shallow borehole and soil samples were collected to monitor moisture changes at various distances in different directions from the injection location. The field results were then used to calibrate a finite element model simulating the field study. The calibrated model was then used to conduct a parametric study varying the soil properties and injection pressures to study the effects on influence distance of injection. Results suggest that, in soils with low hydraulic conductivity, such as in case of expansive soils, high matric suction can result in greater influence distances over time. It was also observed that at this pressure range (0 to 100 kPa), change in pressure of injection had minimal effects on the influence distance. Charts between the influence zone and properties such as permeability, matric suction, and inlet pressures were developed to help plan fluid injections for clays at low pressures.

Introduction

Microbial induced carbonate precipitation (MICP) is a promising soil improvement technique that is cost-effective compared to traditional chemical grouting methods (DeJong et al., 2013). The precipitation of calcite is achieved through a process in which urea hydrolysis is metabolized by soil bacteria to increase the alkalinity of the pore fluid (DeJong et al., 2006; Mortensen et al., 2011). Ureolytic soil bacteria are commonly found in soil environments and can be used for MICP treatments through bio-stimulation; alternatively, ureolytic bacteria can be injected through bioaugmentation techniques (Burbank et al., 2011; DeJong et al., 2013). Several studies have shown the effectiveness of MICP to alter the engineering behavior of sandy and silty soils (Chu et al., 2012; DeJong et al., 2010; Mortensen et al., 2011; Soon et al., 2013). However, studies on clays, and especially on expansive soils, are recent and very limited. Neupane (2016) investigated the use of bioaugmentation to treat low to moderate plasticity clays and found that it could be an alternative stabilizing method for mitigating soil swelling. Touhidul et al. (2020) conducted a laboratory study on eight different types of natural and artificial soils with varying clay contents. Chemical solutions were flushed through soil samples over a period of several days and at multiple intervals to achieve bio-stimulated calcite precipitation and considerable increase in soil strengths and reduction in soil swelling was reported. The same study also found that calcite precipitation increased with increasing clay contents in soils and speculated that MICP is more effective in case of soils containing higher clay contents due to the presence of higher bacterial populations.

In-situ fluid injections were used by Chittoori et al. (2020) in Marsing, Idaho to stabilize expansive soil using bio-stimulation. The field test was conducted by drilling 6.35 cm diameter boreholes at a spacing of 40.6 cm to 76.2 cm into the ground and, injecting one round of bio-enrichment solutions followed by multiple rounds of bio-cementation solutions to stimulate the native bacteria and subsequently achieve calcite precipitation. The injections were done through a pneumatic packer to deliver the solutions to a depth of around 60 cm. During the tests, calcite content and free swelling potential of the soil was monitored by collecting periodic soil samples from the boreholes prior to each injection. The calcite content in the soil increased and the free swelling potential decreased consistently with each subsequent injection of bio-cementation solution. The study demonstrated that microbial induced calcite precipitation could be successfully replicated in the field for the stabilization of expansive soils. However, the lateral penetration distance of chemical solutions in the soil was undetermined and so, a study on the lateral influence distance of the injection method would be necessary to aid future applications in determining an appropriate spacing of injection boreholes.

Therefore, to study the influence distance of fluid injections used in Marsing, Idaho by Chittoori et al. (2020), a numerical simulation was conducted in ABAQUS and verified using moisture change data from a field injection experiment. Injection was conducted in the field by pressurizing water into a borehole beneath a pneumatic packer. Moisture change data was collected from around the injection location to establish an influence distance and numerical simulation was verified against field results. Unsaturated flow was simulated in the numerical model for different soil types by using various soil water characteristic curves and unsaturated hydraulic conductivity properties. The effects of pressure, soil suction, hydraulic conductivity, and injection duration on the influence distance of injections were studied using the model and reported in this paper.

Background

Treatment of expansive soils by pressurized injection into the soil through drill holes or pipes have been used in the past. Pressurized injection of lime to treat expansive soils was discussed by Thompson and Robnett (1976) based on field observations by various other researchers. Pressure injected lime slurry in the subgrade could be forced along fracture zones, cracks, fissures, bedding planes, root lines, coarse-textured seams in varved clays, seams and fractures affected by the pressure slurry injection process, or other passages in the soil mass. It was reported that injection spacings in the rage of 1 to 2 m and pressures in range of 350 to 1350 kPa have been used for treatments in pavement and railroad subgrades, with treatments resulting in varying success rates. It is evident that injections processes are available for treating clays and treatment can be successful in some cases despite their low hydraulic conductivities. A study on the influence distance of pressure injections in low permeability soils is therefore necessary for understanding the possibilities of MICP applications.

To understand the lateral influence distance of fluid injections in soils, an understanding of soil water characteristics and fluid flow through pores is important. The flow of fluids through soil is an incredibly complicated process. Much has been written about the theory of flow through porous media, but natural soils are heterogeneous and consist of haphazard arrangement of pore sizes and distribution, making it difficult to accurately apply such theories. The theories could still, however, be used to get order-of-magnitude data about the effects of changing controllable variables. A form of Darcy's law applicable to grout injections is available in literature that provides a relationship between hydraulic head, discharge, hydraulic conductivity, radius of the injection device, and radius of liquid penetration. In practical use of the relationship, often the radius of liquid penetration is predetermined as part of the injection design and hydraulic head and discharge parameters are checked for safety or economic concerns (Karol, 2003). Truex et al. (2011) used Darcy's equation combined with transient viscosity relationships to plot injection radius and pressure responses in grout injection as a function of time for varying flow rates and highlighted that grout penetration is limited by gelling time and hydraulic conductivity of the subsurface. It can be inferred from the general relationship provided by Darcy's law, that influence distance of fluid injection highly depends on pressure and hydraulic conductivity of the porous medium.

Darcy's law was originally conceived for flow in saturated porous media. Chemical injection processes in semi-arid regions (such as Idaho), especially at shallow subgrade depths, would most likely occur under un-saturated conditions. Darcy's law has been applied to unsaturated flows with an additional provision that hydraulic conductivity applied as a function of matric suction (Hillel, 2008). Matric suction exists due to the physical affinity, between water and the matrix of the soil, which includes both the adsorption of water onto particle surfaces and the attraction of water into capillary pores due to surface tension. When a suction gradient exists in soil, water will be drawn from a zone where the matric suction is lower to where it is higher. The matric suction of the soil can be shown as function of water content (or saturation) in a plot that is known as the soil-water characteristic curve (Tuller & Or, 2005). Fredlund and Xing (1994) have provided an equation for calculating the soil water characteristic curve that is based on the assumption that the shape of the curve is related to the pore-size distribution of the soil. It has been reported that the equation provides a good fit for soils ranging from sands, silts, and clays (Leong & Rahardjo, 1997; Zhai & Rahardjo, 2012). It is necessary to define the soil water characteristic curve for a proper analysis and modelling of unsaturated flow in soils.

A major difference in the saturated and unsaturated flow through any porous media is hydraulic conductivity. The hydraulic conductivity in unsaturated conditions is dependent on the water content of the soil itself, and consequently the matric suction (Hillel, 2008). As soil saturation decreases, a sharp decline in the hydraulic conductivity occurs by up to several orders of magnitude. An equation was proposed by Fredlund, Xing, and Huang (1994) to predict the hydraulic conductivity function for unsaturated soils based on the soil water characteristic curve. It was reported that the equation provided an excellent fit between data and theory and was able to integrate hydraulic conductivities for soils from zero to maximum water contents. Incorporating a saturation (or suction) dependent relationship for hydraulic conductivity into Darcy’s law can model a steady-state unsaturated flow process. In practice however, chemical injections into the soil is a transient process (Karol, 2003).

Transient unsaturated flow is fundamentally different than saturated flow and steady-state unsaturated flow. During transient unsaturated flow, water enters pores that were previously occupied by another fluid. Typically this fluid is air; it is commonly assumed that the displacement of the resident air does not impede the advance of water into a pore (Ferré & Warrick, 2005). This underlying assumption is also used in Richards equation, a special expression that describes the movement of water through an unsaturated porous medium (Ferré & Warrick, 2005; Hillel, 2008). Richards equation combines the equation of for mass conservation to that of Darcy’s law with added provision for saturation dependence of hydraulic conductivity. The equation is highly nonlinear because of the interdependence of parameters involved (namely, the dependence of both the water content and the hydraulic conductivity on the soil's matric potential) and cannot be solved analytically. Numerical methods are required to successfully model transient fluid flow in unsaturated soils. Hence, this study aims to understand the influence distance of fluid injection in low permeability soils through experimental and numerical models.

Field Study

A field study was conducted in Marsing, Idaho to establish an influence distance of in-situ fluid injections, and to aid in the verification of numerical model used for further study. Data collected following a fluid injection was interpolated to plot a contour of moisture changes around the injection borehole, and influence distance was defined based on a specific change in moisture content around the injection point.

Equipment and Injection Setup

The equipment used in the field injection test included a handheld power auger (to drill a borehole), a pneumatic packer system (to seal the borehole), a water tank with hydraulic pump (to inject water), and a manual hand auger (to collect samples from different depths). The water pump used in this study could be operated in the field by connecting it to a 12V car battery. The water pump had a rated capacity to pump 5.5 gallons (20.8 liters) per minute (20 liters per minute) at a pressure of 60 psi (413.7 kPa). A PVC Tee connection was attached at the outlet of the pneumatic packer such that the water flow would occur laterally away from the packer tube. The injection packer and field setup used for the study are shown in Figure 0.1, in addition to a schematic of the injection in Figure 0.2.a.

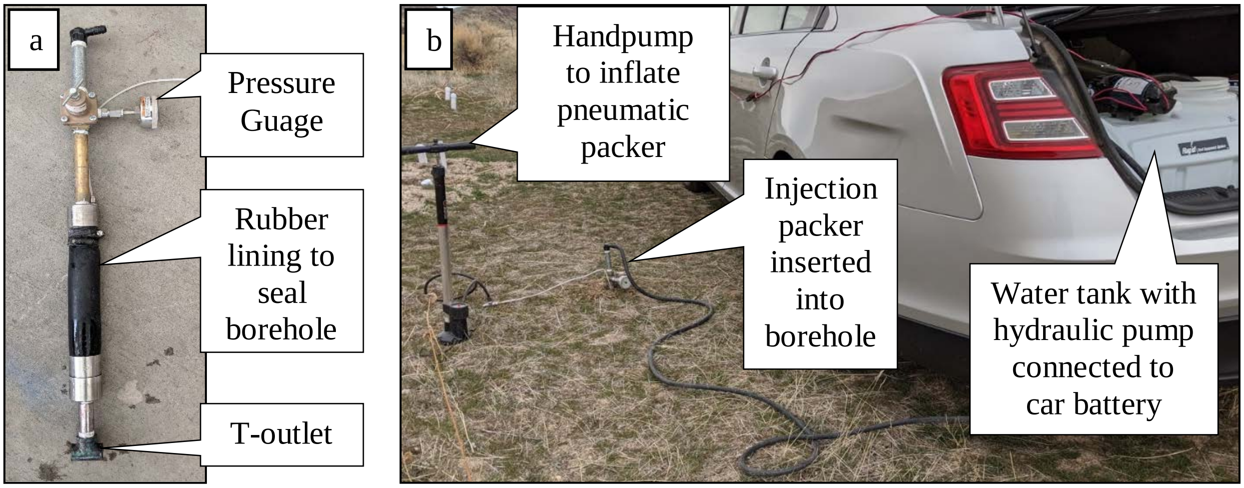
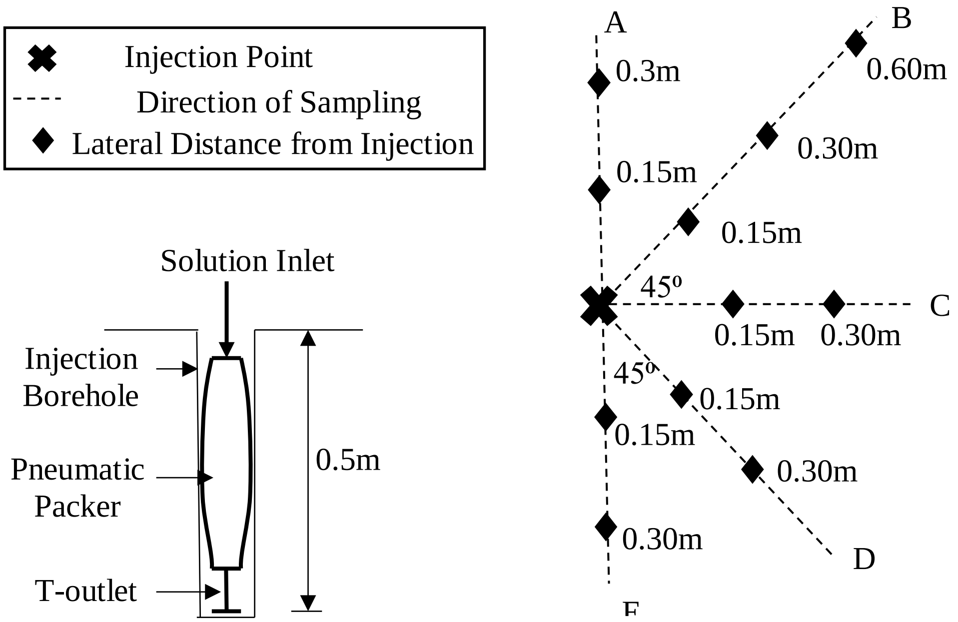


Figure 3.1. Equipment and Setup - (a) Injection Packer (b) Injection Setup in Field



a. Injection Schematic

b. Moisture Sampling Layout

Figure 3.2. Injection Schematic and Lateral Layout of Moisture Sampling Around Borehole

Field Injection and Moisture Sampling

Before the injection was performed, soil samples were collected at various depths from the injection borehole and a location 60 cm away from the injection point to measure the baseline moisture content. The injection was conducted through a 50 mm diameter borehole and soil samples were collected from along various directions around the injection point using a manual hand auger (see Figure 0.2.b for sampling locations). A symmetric distribution of moisture on either side of the T-outlet axis was assumed and samples for moisture change data was collected from one side of axis A-E (direction of T-outlet) shown in Figure 0.2.b.

The injection was conducted at a pressure of 34.5 kPa (5 psi) and continued for a duration of 2 minutes. The packer outlet was positioned at a depth of 0.5 m during injection. Injection was stopped when water started overflowing to the surface from the borehole. Soil samples were collected at specific depth intervals around the borehole, starting from ground surface to the maximum depth of 70 cm. The moisture content in soil after injection was determined by drying the samples to a constant weight in an oven at 110°C.

Field Observations

The increase in moisture content of soil around the borehole, after the injection, was interpolated using the spatial moisture data and a lateral moisture change contour could be plotted at various depth intervals. It was observed through the plots that, the lateral influence of injection varied in direction and depth around the borehole. Furthermore, it was observed that the moisture change around the injection point occurred along the entire length of the borehole – even at the location of the pneumatic packer seal. When refusal of injection occurs, and water starts flowing back to the surface from along the surface of contact between the pneumatic packer and the soil, moisture can travel laterally into the soil until supply is stopped. A boundary was plotted around the injection point (see Figure 0.3), to represent a 5% increase in moisture content of the soil (equivalent to a 10% increase in saturation for the Marsing soil). This boundary was considered the zone of lateral influence of the injection point in this study.

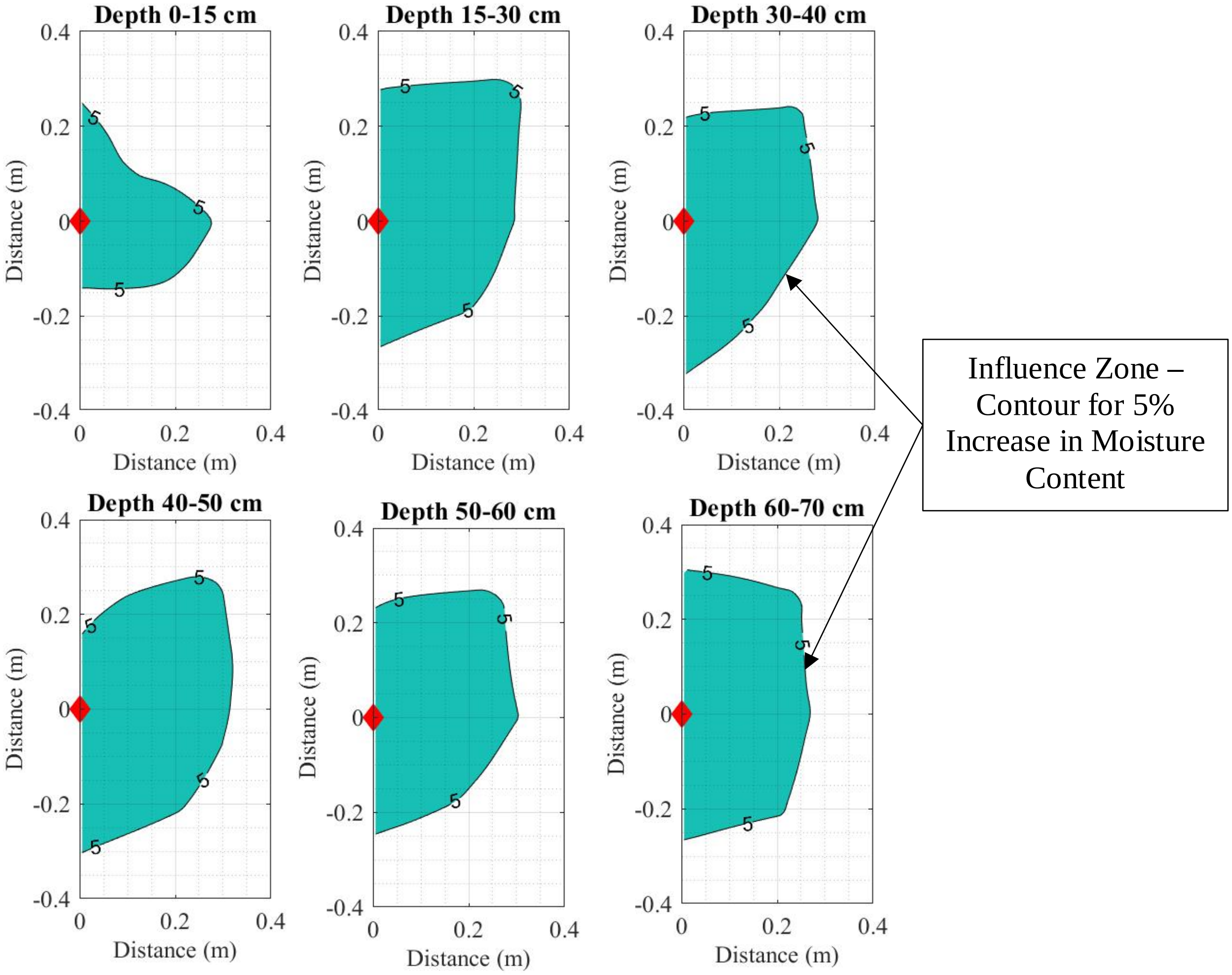


Figure 3.3. Influence zone of single point injection (Contour at 5% increase in moisture)

An average radius of influence around the injection point was calculated from the boundaries obtained in Figure 0.3 by equating the area of influence around the borehole to that of a semi-circle. Considering the radius of influence within the 15 to 70 cm depth, average radius of influence was estimated to be 0.27 m.

This observation suggests that, in Marsing, injection boreholes would have to be spaced within approximately 0.5 m for application of MICP using this injection method. For application purposes of MICP, assuming that a similar effect in saturation of the soil is obtained at a point, a lateral influence from four injection boreholes would result in a

40% increase in saturation. Additional studies will be needed to verify if such an increase in saturation would be effective enough for a desired level of improvement in soil properties through MICP. The study is out of scope for this paper.

Numerical Modelling

A finite element model was constructed in ABAQUS to simulate the in-situ fluid injection performed in Marsing, Idaho. ABAQUS is a finite element software with built-in features that enables a user to perform transient seepage analysis in unsaturated soil conditions using a continuum soil model. A finite element model was built using soil properties of Marsing soil (see Table 0.1) and simulation of fluid injection in the model was verified using the average radius of influence obtained from the field. The properties used in the model were then modified to simulate injection in other soil types, and to study the effects of pressure, hydraulic conductivity, and soil suction on the influence distance of injection.

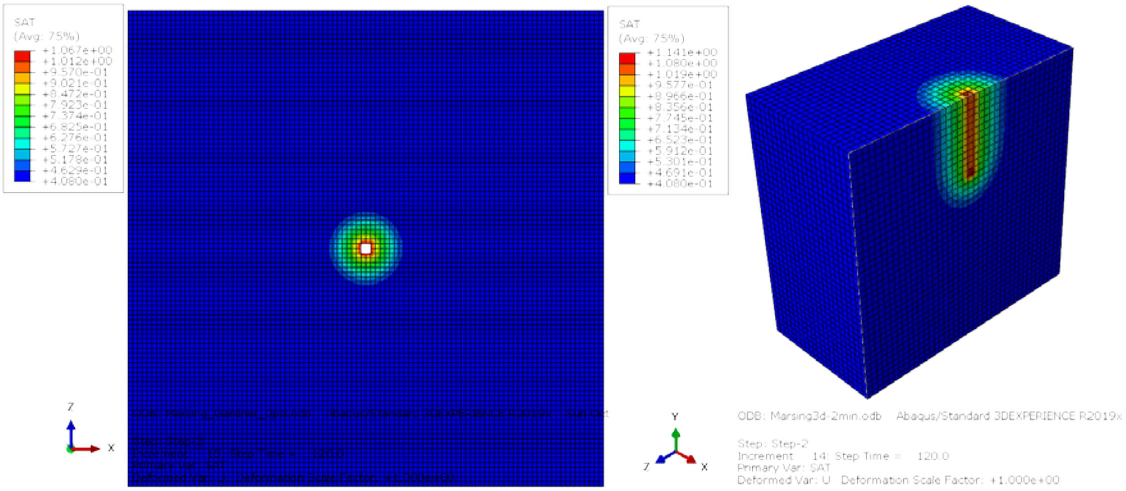
Table 3.1. Properties of Marsing Clay

Dry Density (kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Specific Gravity	Void Ratio	Hydraulic Conductivity (m/s)	Initial Saturation	Air Entry Value (kPa)
1263	146	0.4	2.69	1.1	5.30E-07	41%	637

Model Properties and Analysis Procedure

Fluid injection in the model was simulated by applying a positive pore pressure boundary condition inside a 5cm x 5cm cut at the center of the model. Pore pressure boundary conditions of 0 kPa, 34 kPa, 69 kPa and 103 kPa (0 psi, 5 psi, 10 psi and 15 psi) were used to simulate various injection pressures in the model. In addition, a displacement boundary condition was applied at the edge of the model to restrict lateral movement. The model analysis was run under transient conditions for a duration of 2 minutes and a distance vs. saturation curve was obtained from the results of the simulation. The influence distance for a simulation was obtained by measuring the distance from the center of the model that corresponded to a 10% increase in initial saturation.

Initially, a comparison between a 3D (2m x 2m x 2m in size) vs. a 2D (2m x 2m) model was made based on influence distances obtained from the simulation. Figure 0.4 shows the 2D and 3D models with colored contours representing soil saturation at the end of 2 minutes. The influence distances obtained from the 3D and 2D models (at the end of 2 minutes) varied only by 1 cm. However, the 3D simulation took a significantly high amount of computational time (approximately 2 hours). A radius of influence of 0.28 m was obtained from the 2D model (only 1 cm higher than the equivalent radius of influence obtained from the field observations). To save computational time, the 2D model was selected for additional injection simulations.



a. 2D Model

b. 3D Model

Figure 3.4. ABAQUS model simulation results showing saturation contours for Marsing soil after 2 minutes

Table 3.2. Soil properties used in ABAQUS model

Soil	Hydraulic Conductivity, k (m/s)	Air Entry Value, AEV (kPa)
Marsing	5.30E-07	637
S1	3.80E-05	0.7
S2	3.80E-05	6
S3	3.80E-05	58
S4	3.80E-05	504
S5	6.60E-06	0.3
S6	6.60E-06	2
S7	6.60E-06	26
S8	6.60E-06	202
S9	6.60E-06	1746
S10	4.15E-07	0.8
S11	4.15E-07	8
S12	4.15E-07	30
S13	4.15E-07	151
S14	4.15E-07	2723
S15	4.15E-08	30
S16	4.15E-08	151
S17	4.15E-08	2723
S18	4.15E-09	30
S19	4.15E-09	151
S20	4.15E-09	2723

Soil properties for the Marsing soil were obtained using data from field samples, existing laboratory studies, or estimated through the SOILVISION^{TM} software. A Shelby tube sample obtained from the injection site was used to estimate the field density, void ratio, and initial saturation of Marsing soil. Elastic properties for the soil - Young's Modulus and Poisson's ratio, and the soil water characteristic curve (SWCC) were obtained from existing laboratory data (Tamim, 2017). Saturated and unsaturated hydraulic conductivity for Marsing soil was estimated using SOILVISION^{TM} software. Hydraulic conductivity (5.3x10^{-7} m/s) obtained using Rawls et al. (1993) method in SOILVISION, which uses the grain size distribution (5% sand, 26% silt and 69% clay) and porosity of the soil, was used for modelling in ABAQUS. Rawls, Brakensiek, and Logsdon (1993) developed a method for estimating saturated hydraulic conductivity of soils by modifying the Marshall (1958) saturated hydraulic conductivity equation and reported that the method could reasonably predict hydraulic conductivity for a wide range of soil types (including clays). Other methods of estimation available in SOILVISION have limitations of use based on grain sizes and are mostly suitable for coarse grained soils. The value of hydraulic conductivity predicted using SOILVISION seems suspiciously high for typical clay soils but field measured hydraulic conductivities ranging in the order of 10^{-6} to 10^{-8} have been reported for clay soil with similar grain size distribution (Lee et al., 1985). Although, a much lower order of magnitude of hydraulic conductivity can be expected for a well compacted sample of clay, presence of fissures, cracks and root networks in field conditions may result in a higher effective hydraulic conductivity for an overall mass of soil. Field hydraulic conductivities of up to 4 orders of magnitude higher than laboratory measured values has been reported (Hanor, 1993). In addition, since the field results of the injection and the numerical simulation results from ABAQUS agree with the estimated order of the hydraulic conductivity for soil from test site in Marsing, the predicted hydraulic conductivity can be considered reasonable for this study.

Additionally, the unsaturated hydraulic conductivity was estimated using the Fredlund, Xing, and Huang (1994) method. The SOILVISION^{TM} software was also used to generate saturated and unsaturated hydraulic properties for other soil types. The Fredlund and Xing (1994) method for modelling a soil-water characteristic curve can be used to generate a wide range of suction properties for various soil types. Various suction curves generated using this method and along with various hydraulic conductivities were inputted in the ABAQUS model to simulate injection in other soil types. The various soil properties used in this study are as shown in Table 0.2. Air Entry Value (AEV) is defined by Fredlund and Rahardjo (1993) as the matric suction value that must be exceeded before air recedes into the soil pores. AEV obtained from each soil water characteristic curve was used as the defining parameter for soil sorption in this study and was used to compare influence distance plots.

Results of Numerical Simulation

Soil saturation results obtained from 2D models were used to compare the effect of hydraulic conductivity, soil suction and pressure changes on the influence distance of injection. The effect of a longer injection duration on influence distance was also studied.

Effect of Hydraulic Conductivity and Matric Suction

Variation in influence distance with hydraulic conductivity and air entry values were plotted as shown in Figure 0.5 and Figure 0.6. As expected, the results show that increase in hydraulic conductivity of the soil would result in higher influence distances of the soil. Similarly, influence distances are higher for soils with higher air entry values. When increasing suction properties are assigned to the soil model, larger influence distances are realized due to the presence of a high-pressure gradient away from the injection point (point of positive pore pressure). Based on Figure 0.5, it can be seen that influence distances of 20 cm or higher could be achieved in soils with air entry values higher than 100 kPa, even at low hydraulic conductivity of the order 10^{-7} m/s.

Effect of Injection Pressure

The effect of change in injection pressure on influence distance, for varying hydraulic conductivities and air entry values, is shown in Figure 0.7. Within the range of pressures used in this study (0 to 103 kPa), increasing pressure had little to no effect in influencing distance of moisture increase for soils with low hydraulic conductivities (on order of 10^{-7}). An increase in injection pressure seems to have a higher effect in increasing influence distances for low suction and high permeability soil (see Figure 0.7 for k = 3.8e-5 m/s, AEV = 60 kPa). For soils with high matric suction values (greater than 100 kPa), which can be typically expected in clays, the role of pressure changes seems insignificant. This could be because the range of pressures used in this study are not significant enough to result in a change in pressure gradient that would result in a visible yield of influence distances. This suggests that spacing of the injection points should be determined based on the hydraulic conductivity and suction properties of the target soil, regardless of the injection pressure, for soils with very low hydraulic conductivities. For soils, with larger hydraulic conductivities in the order of 10^{-5} m/s, pressures may be increased to increase the spacing of injection points.

Effect of Duration of Injection

Influence zone increased with time of exposure to a given pressure as shown in Figure 0.8. The influence distance vs time for a given soil model could be correlated with power functions with R^2 values of 0.99. The relationships shown in the chart may be used to determine injection spacing for similar soil types. Since it has been established that increasing the pressure of injection has little to no effect in influence radius, maintaining a low-pressure head in a borehole (possibly with the injection solution exposed to atmospheric pressures) and letting the moisture soak into the subgrade for longer durations could result in a high zone of influence. Distance between injections boreholes may be increased by using a longer time duration. Given that MICP is a time-consuming process, with wait periods between injections spanning several days (Chittoori et al., 2020; Touhid et. al. 2020), this could possibly be a better approach to implementing MICP instead of pressure injections. The chances of hydrofracturing the soil is also eliminated by using low-pressure injections.

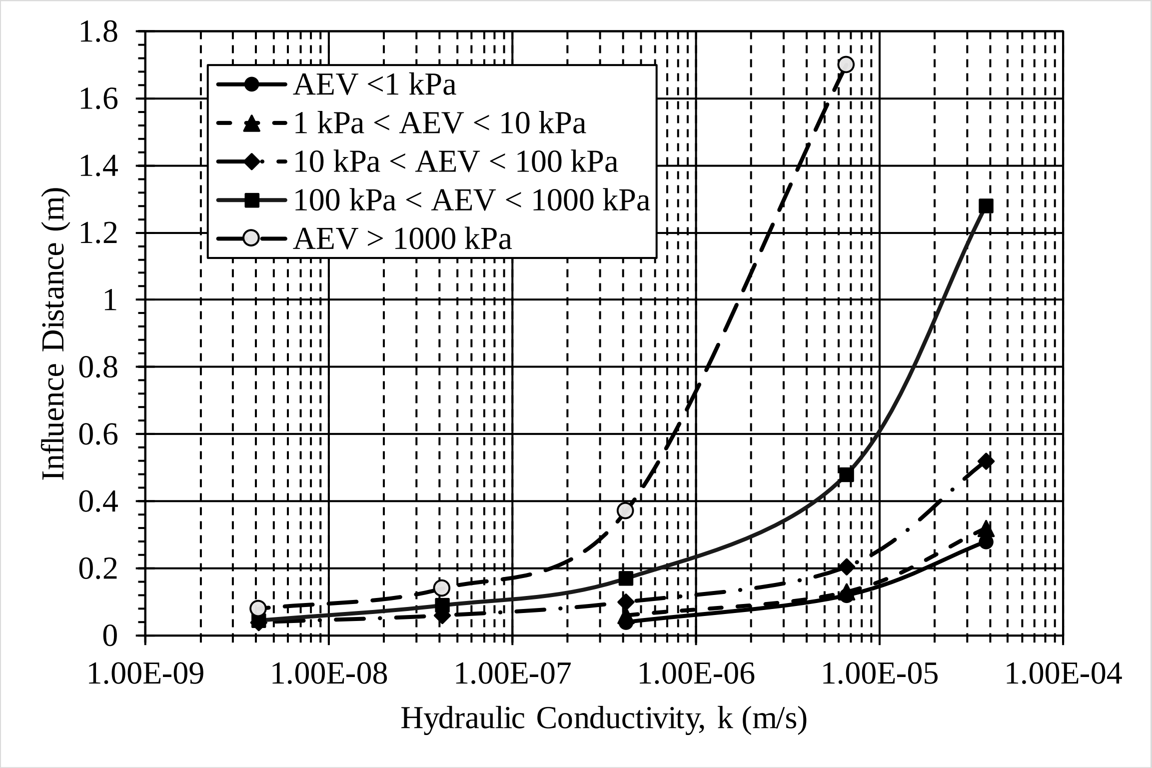


Figure 3.5. Influence Distance (at 2 minutes) vs. Hydraulic Conductivity

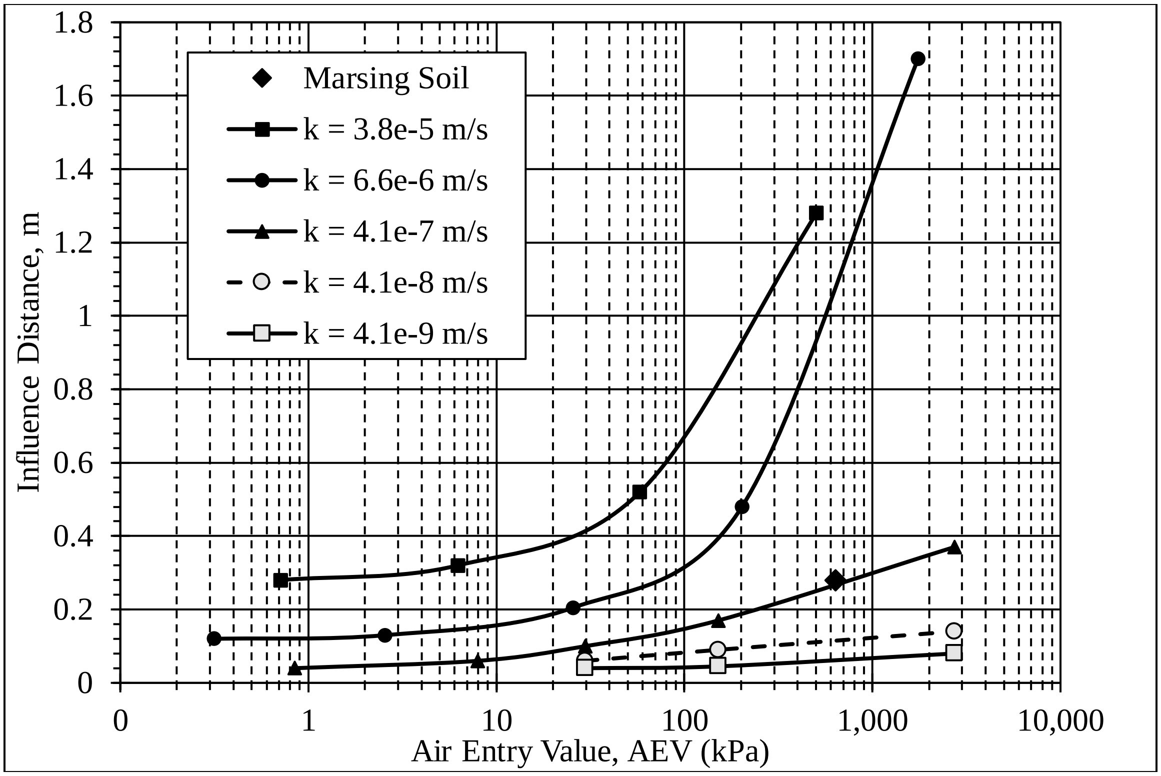


Figure 3.6. **Influence Distance (at 2 minutes) vs. Air Entry Value**

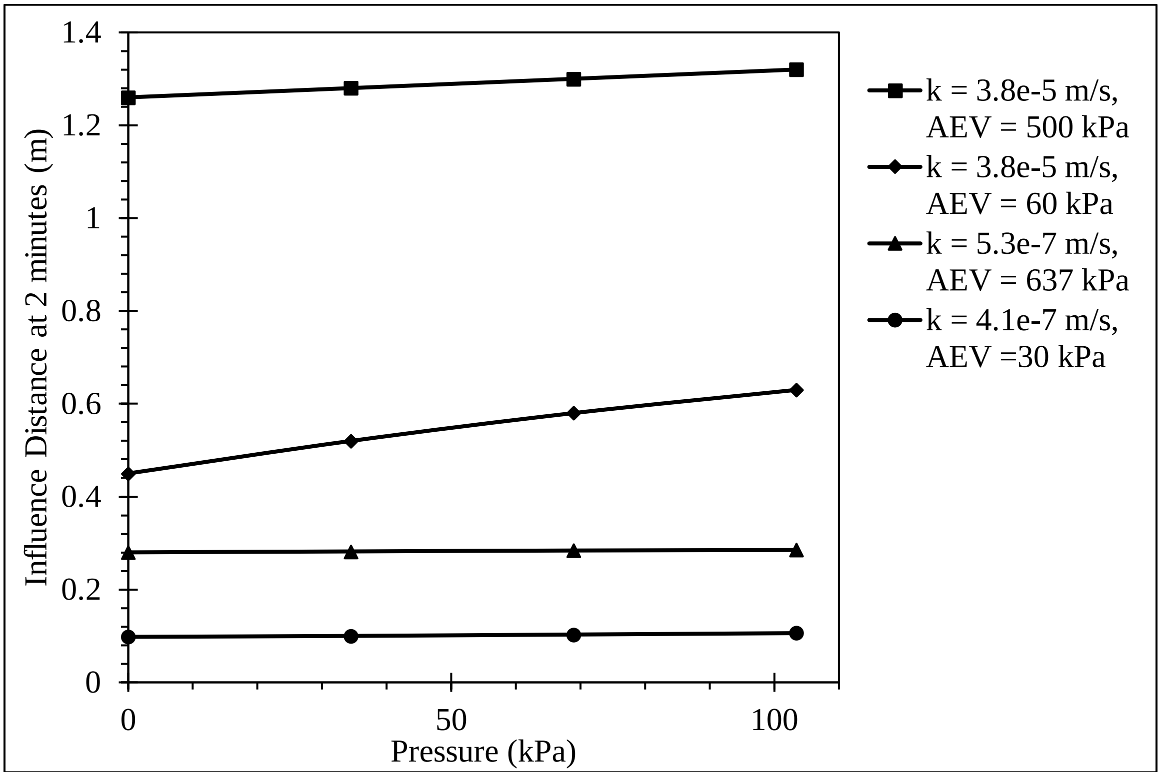


Figure 3.7. **Influence Distance (at 2 minutes) vs. Pressure**

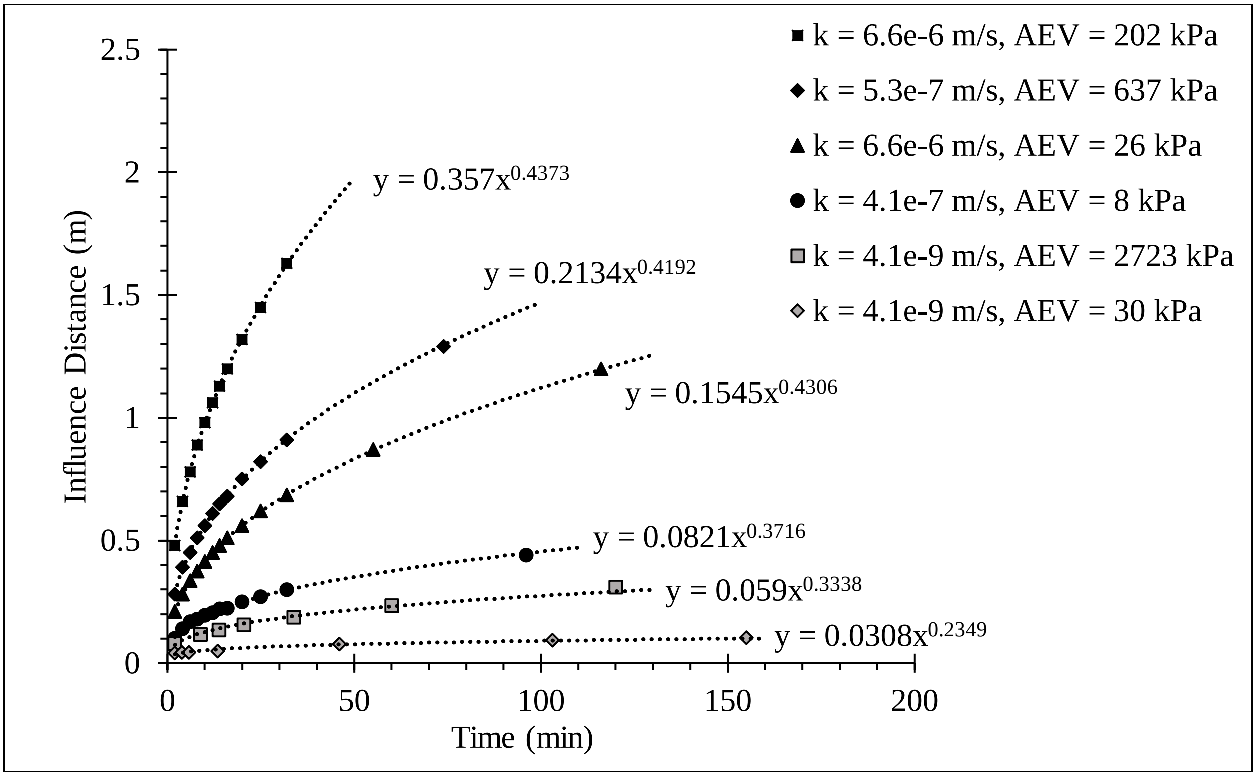


Figure 3.8. Influence Distance vs. Duration of Injection

Conclusions and Recommendations

It was evident from the results of field injection in Marsing, Idaho that a uniform distribution of solution into a clay soil may not be achieved around a borehole. The influence zone can vary widely in vertical and lateral directions around the injection borehole. The distances between injection boreholes may have to be 0.5 m or less to treat subgrade soils like Marsing clay. Such a low spacing between injection boreholes can have an adverse effect in the strength of the soil subgrade. However, it was seen in the results of numerical analysis that if the injection duration can be increased, larger influence distances may be achieved.

Numerical results also showed that pressure is insignificant in changing the lateral influence distance for low hydraulic conductivity soils. Results obtained from numerical studies suggest that solutions used in MICP applications may be pushed farther around the injection borehole by maintaining a constant supply of chemical solutions even at low pressures. For future studies of MICP in fine-grained soils, it is recommended that a system for long-duration and low-pressure delivery of solution be used. Injection boreholes could possibly be spaced at up to more than 2 meters if injection can be maintained for durations of more than 2 hours in soils with properties like Marsing clay. For soils with higher hydraulic conductivities (in order of $1\text{x}10^{-5}$ m/s), where increased pressure of injection can result in a larger influence distance, a much higher distancing may be used.

In this paper, it is assumed that a 10% increase in saturation by injection in one neighboring borehole is enough for the implementation of MICP. Further investigation will be necessary to verify if this assumption is applicable in nature, and to determine the optimum amount of saturation or concentration of chemicals that will be necessary to achieve MICP in soils. Future research in this novel field of MICP application could ultimately lead to a revolutionary and eco-friendly method for dealing with problematic soils.

CHAPTER FOUR: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary and Conclusions

This research investigated the process of in-situ chemical injections for implementation of Microbial Induced Calcite Precipitation in expansive and low permeability soils. The investigation was conducted in two phases. First, with the objective of determining the feasibility of precipitating calcite (through MICP) in the field using pressurized chemical injections, chemical solutions were injected into the ground through shallow boreholes in Marsing, Idaho to achieve bio-stimulated calcite precipitation in an expansive clay. Four rounds of chemical injections were conducted, and soil samples were collected from the injection locations to monitor changes in calcite contents and swelling potential of the soil. Considerable increase in calcite content and reduction in swelling potential was observed through laboratory tests conducted on treated soil samples. The lateral influence distance of the chemical treatments was not known during the study and so had to be established for the design of injection systems for future implementations. Therefore, the second phase of study was conducted with an objective to understand the lateral influence distance of fluid injections in the soil. Experimental and numerical investigation was used to establish an influence distance and to study the effects of pressure, permeability and soil suction in the influence zone. In-situ injections were performed in a clayey soil through a shallow borehole and soil samples were collected to monitor moisture changes at various distances in different directions from the injection location. The field results were used to calibrate a finite element model simulating the field study. The calibrated model was then used to conduct a parametric study varying the soil properties and injection pressures to study the effects on influence distance of injection.

Major findings from this study are listed as follow:

1. It was witnessed during in-situ application of MICP that, the calcite content increases significantly with each successive injection of cementation solution and reduces swelling potential of the soil. Calcite precipitation increased with treatments (up to 8% total) and the free swell index dropped from 114% to 29%.
2. Field investigation on the influence zone of pressure injection showed that a uniform distribution of solution into the soil may not be achieved around an injection borehole. The influence zone can vary in vertical and lateral directions around the injection borehole. On average, a lateral influence distance of 0.27m was estimated for injections in Marsing clay. This means the distances between injection boreholes may have to be 0.5 m or less to treat subgrade soils like Marsing clay (which had hydraulic conductivity in the order of 10^{-7} m/s and matric suction of 637 kPa).
3. Results of numerical investigation showed that pressure, in the range of 0 to 100 kPa, is insignificant in changing the lateral influence distance for low hydraulic conductivity soils. Additionally, it was seen that higher influence distances can be achieved in soils with high permeabilities and matric suction values.

4. It was noted from the results of numerical simulation that influence distances can increase over time under constant supply of injection head. Results obtained from numerical studies suggest that solutions used in MICP applications may be pushed farther around the injection borehole by maintaining a constant supply of chemical solutions even at low pressures.

Recommendations

There are several scopes that could be considered for furthering the process of implementing bio-stimulated calcite precipitation in fine grained soils. Some future research recommendations are enumerated as follows.

1. During the field investigation of MICP, calcite precipitation was found to increase with each round of treatment for Marsing clay. Additional soil types may be studied with varying concentration of chemicals and number of injections to establish an optimum method for bio-stimulated treatment process.
2. To verify the conclusions based on numerical investigation done in this research, it is recommended that a system for long-duration and low-pressure delivery of solution be used to implement MICP. Injection boreholes could possibly be spaced at up to more than 2 meters if injection can be maintained for durations of more than 2 hours in soils with properties like Marsing clay. For soils with higher permeabilities (in order of 1x10-5 m/s), where increased pressure of injection can result in a larger influence distance, a larger distancing may be used.

3. In this study, it is assumed that a 10% increase in saturation by injection in one neighboring borehole is enough for the implementation of MICP. Further investigation will be necessary to verify if this assumption is applicable in nature, and to determine the optimum amount of saturation or concentration of chemicals that will be necessary to achieve reasonable benefits from MICP applications. Future research in this novel field of MICP application could ultimately lead to a revolutionary and eco-friendly method for dealing with problematic soils.

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