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ENJEKSİYON PARAMETRELERİ VE TEKNİKLERİNİN HOMOJEN ZEMIN BİO-İYİLEŞTİRMESİNE ETKİSİ: BÜYÜK ÖLÇEKLİ BİR DENEYDEN GÖRÜŞLER

ON THE EFFECT OF INJECTION PARAMETERS AND TECHNIQUES TOWARDS ACHIEVING HOMOGENOUS SOIL BIO-IMPROVEMENT: INSIGHTS FROM A LARGE-SCALE EXPERIMENT

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ABSTRACT

Microbially Induced Calcite Precipitation (MICP) utilizes soil microorganisms to precipitate calcium carbonate minerals, which serve as binding elements for soil improvement applications. However, achieving precipitation homogeneity throughout the targeted soil volume can be challenging and requires experiments at a scale which can be considered representative of typical geotechnical works. This study focuses on understanding the effect of different injection methods and parameters on the spatial distribution of calcium carbonate precipitates in sand and on proposing a suitable soil treatment protocol for MICP applications. This large-scale experiment is carried out on 80m^3 of 0-4mm sand via alternative injection methods, including, among others: (i) the use of double packers similar to those commonly applied for cement grouting; (ii) the use of permeation grouting methods; (iii) the application of various treatment protocols, to ultimately allow a comprehensive comparison of the effectiveness of each technique. Continuous quality control and injection monitoring, including in-situ piezometers and fixed sampling points for chemical analyses, are further performed to enable the quantification of parameters linked to the temporal and spatial evolution of MICP. The outcomes identified in this work can serve as a reference for implementing successfully field-scale applications of soil bio-improvement or calibrating numerical models which aim to simulate the MICP process.

Keywords: *MICP treatment; soil improvement; homogeneity; injection techniques*

1. INTRODUCTION

In geotechnical engineering, the quest for sustainable alternatives to conventional soil improvement methods has increased the interest in MICP over the last two decades. Since its inception in the literature nearly twenty years ago, MICP has garnered attention as a promising approach for enhancing soil properties, offering a potential replacement for traditional techniques. By harnessing the capabilities of specific microorganisms to provoke the precipitation of calcium carbonate within soil pores, MICP contributes to increased soil strength and improved overall stability, thereby revolutionizing soil improvement practices.

The efficacy of MICP hinges on many interrelated factors, spanning the selection of microorganisms, the uniformity of soil improvement, the intrinsic attributes of the soil matrix, and the rigorous application of quality control protocols. Extensive investigations have predominantly spotlighted *Sporosarcina pasteurii* as the microorganism of choice for initiating urease-driven reactions. Its non-hazardous nature, ease of cultivation, and remarkable adaptability to diverse environmental conditions have positioned it as a front-runner in MICP endeavors (Harran et al., 2023). Moreover, its ability to adhere to grain surfaces bolsters urease activity, resulting in a profusion of stable calcite precipitates, thus consolidating its standing as a pivotal agent in MICP applications.

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In the context of large-scale field implementation, a critical challenge emerges—ensuring the homogeneity and durability of MICP-treated soils. A comprehensive overview of pioneering studies in the field is described in Terzis and Laloui (2021) with the majority of available works focusing on highlighting the role of mixing conditions of bacteria, nutrients, urea, and calcium sources in attaining uniform soil treatment at the scale of typical geotechnical laboratory testing. The chosen injection techniques, encompassing variables such as injection rate, pressure, and spacing, intricately govern the extent of dispersion of microbial solutions and calcium sources within the soil matrix, resulting in bio-cementation. Moreover, the interplay between soil properties—ranging from particle size distribution and permeability to porosity influences the interaction between injected solutions and soil constituents. Understanding these properties is a prerequisite for tailoring MICP strategies to the distinct attributes of specific soil types, ensuring optimal treatment outcomes. Against this backdrop, the present study endeavors to unravel the optimal injection parameters and tube configurations that facilitate the most efficacious and uniform improvement of sand under unsaturated sand conditions.

2. MATERIALS AND METHODS

2.1. Installation

In this study, a 70m³ reinforced concrete basin was utilized to investigate soil behavior using the MICP technique. In order to maintain an unsaturated state, eight drainage tubes were positioned along the bottom surface of the tank allowing drainage towards a ditch positioned outside of the side wall of the basin. The experimental medium chosen was sand with a granular class of 0/4mm, filled at a target porosity of 30%.

a) b) (c) (d) (e)

Figure 1. a) The reinforced concrete basin, b) Types of tubes, c) Filling of sand in layers, d) Injection with double packer, e) Measurement setup

Preceding the placement of sand, a 15cm layer of gravel drainage was established and covered with a layer of geotextile material (as shown in Figure 1a). This dual-purpose geotextile served the functions of drainage facilitation and prevention of sand migration into the underlying gravel layer. For the MICP treatment, a total of 6 injection tubes were employed. Among these, three adhered to the conventional tube-a-manchette (T.A.M.) design, each measuring 2.25m in length and with a diameter of 28/32mm. The remaining three tubes had distinctive configurations: T.A.M. tubes with slits, T.A.M. tubes with softer sleeves, and a steel injection tube (as depicted in Figure 1b). The positioning of the tubes was integrated during the incremental layering of sand (as illustrated in Figure 1c). To monitor soil pressure during the injection procedures, nine pressuremeter probes were strategically placed at varying depths adjacent to the second injection well. The double inflatable packer was chosen to ensure uniform distribution of the solution introduced into the soil through each port. Both injection lines were equipped with a manometer and a water counter, enabling the continuous monitoring and recording of injection pressures, flow rates, and flow amounts. Various parameters, such as the number of cycles, flow amounts, flow rates (pressure), and different injection tubes, were utilized during the experiment. The summary of the parameters can be seen in Table 1.

2.2. Preparation and Injection of the Mixing Solution

The mixtures utilized in the experiment comprises two distinct solutions: the Bacterial Solution (BS) and the Cementation Solution (CS). The BS includes *S. pasteurii*, soy peptone, urea, and water, while the BS consists of $CaCl_2$, urea, and water.

Table 1. Injection Parameters applied at different injection wells

Injection Wells	Type of Injection Tube	Distance between ports on tubes	Cycles		Flow (l/min)		Pore Volume x (…)
			BS	CS	BS	CS	
1	T.A.M. tube	50cm	1	1	1,5	1,5	1,25
2	T.A.M. tube	50cm	1	1	1,1	1,1	1,70
3	T.A.M. tube	50cm	1	3	7,0	7,0	1,25
4	Tube with Slits	5cm	1	1	10,0	10,0	1,25
5	Steel tube	25cm	1	1	14,0	10,0	1,25
6	T.A.M. tube with softer sleeves	50cm	1	1	7,0	7,0	0,95

The BS contains the necessary components to foster the growth and activity of *S. pasteurii*. The CS, on the other hand, provides the necessary compounds for calcium carbonate precipitation (Table 2.) Following the preparation of the agents for the BS in 1m^3 (IBC) tanks, the solution was allowed to undergo a mixing process under air stirring for 72 hours. Throughout this mixing period, samples were periodically collected, while pH values and conductivity measurements were documented. After a one-day interval following the completion of the BS injection, the CS solution was prepared and injected into the designated well. This interval was implemented to allow the BS mixture sufficient time to attach to soil particles. The injections were directed into the soil through different types of injection tubes, as specified in Table 1. These unique tube variations were selected to examine their effects on the distribution and behavior of the injected solutions within the soil structure.

Table 2. Treatment solutions constituents.

AGENTS	BS	CS
Peptone (kg/m^3)	1	-
Bacteria (l/m^3)	10	-
Urea (kg/m^3)	20	60
Calcium Chloride (kg/m^3)	-	10

In addition, a double-packer system was utilized for the injections. Before the injection, the packer was positioned, and the rubber membranes were inflated with water. Afterward, the solution was pumped from the tanks to the ports of the injection tubes using a pump, hoses, and the packer. The valves were configured to ensure the desired flow rate during the injection, and the injection process was continually monitored.

2.3. Dynamic Penetrometer Readings

A dynamic penetrometer (Panda, Solsolutions) was employed to assess the soil improvement resulting from the injections. This instrument measures the resistance of the soil as it penetrates the ground, providing valuable data on soil characteristics. Prior to the injections, penetrometer readings were taken at various locations in the concrete basin to establish a baseline of the tip resistance of the untreated sand for comparison after the improvement. Following the completion of the injections, soil testing was carried out around each injection axis at two distinct distances: 12 cm and 25 cm. These tests were conducted in four directions: North, South, East, and West. Subsequently, the data collected from the dynamic penetrometer tests were compared. This comparison aimed to evaluate both the radial homogeneity of the soil improvement and its vertical homogeneity.

3. RESULTS

The detailed tip resistance diagrams for all wells are presented in Figure 2. for all directions and distances from the injection axis. Results are discussed per injection well as follows:

3.1. Injection Well 1

It's evident that the boundary conditions at the top and bottom of the fill, along with surface settlement occurring during injections, have reduced the thickness of the layer above the first port, causing pressure release and fluid escape. This, in turn, results in lower improvement in those areas. The surface settlement is believed to be due to the rearrangement of sand upon the pressurized introduction of the first batch of the treatment solution. The study revealed a noticeable improvement within a limited range of 12 cm, showcasing resistance levels ranging from 4 to 8 MPa. However, achieving uniform improvement across the entire depth proved challenging. Evident peaks were discernible at the port levels, suggesting variations in the treatment level. While radial homogeneity was generally achieved, an exception arose in one direction (yellow curve) where the pressure might not have been adequate to open the sleeve, leading to some deviations from the expected results.

3.2. Injection Well 2

Even though a larger quantity of solution was injected, there wasn't a significant difference in improvement compared to the first borehole. This could be attributed to the low flow rates, which may have led to the migration of solution due to gravity flow towards the draining bottom, before it could reach a sufficient distance. Improvement was observed exclusively within a 12 cm radius, displaying resistance levels above 2 MPa. However, attaining uniformity across the entire depth proved unattainable. Evident peaks surfaced at the port levels, indicating disparities. Nevertheless, radial homogeneity was realized, with relatively consistent values at equivalent depths across various directions. It was understood that the 1 – 1.5 liters/min flow rate was insufficient to improve further than the equivalent column of a diameter of 25 cm.

3.3. Injection Well 3

While no improvement was observed at 25cm distance for wells 1 and 2, this was achieved for the third well. This could be attributed to the higher pressure and flow rate employed. In addition, using three cycles of CS resulted in greater improvement values, reaching up to 20 MPa in a 12cm radius. Soil improvement was observed within a radius of 25 cm, encompassing a tip resistance range between 4 and 5 kPa. Distinct peaks became evident at the port level, specifically at a radius of 12 cm. Achieving greater uniformity across the depth was realized when considering a radius of 25 cm. The injection ensured radial homogeneity, with consistent outcomes across different directions.

3.4. Injection Well 4

A uniform treatment was achieved within a 12cm radius. Additionally, homogeneity is apparent between the initial 70cm depth and the rest, from 70 cm to 140 cm, measured at 25cm from the injection well. The differentiation between these zones can be attributed to backflow at the surface. Significantly, the pressure relief at the surface did not affect the improvement within the 12cm zone, as the pressure in that region was already adequately high. For Well 4 improvement is captured within a radius of 25 cm, with a resistance of 3 MPa, but in contrast to what was observed for previous wells, no significant peaks were detected at the level of the injection ports this time. Rather, an enhanced consistency across the depth was realized at radii of both 12 and 25 cm. While radial homogeneity was almost achieved, the level of resistance increased did not match that observed for other wells. This could be attributed to the specific type of slit pipes manufactured for the purpose of this study.

3.5. Injection Well 5

The steel rod was raised at intervals of 25 cm during injection, and the soil was evenly injected through the depth While complete homogeneity wasn't achieved, noteworthy improvement rates were still observed with this alternative setup.

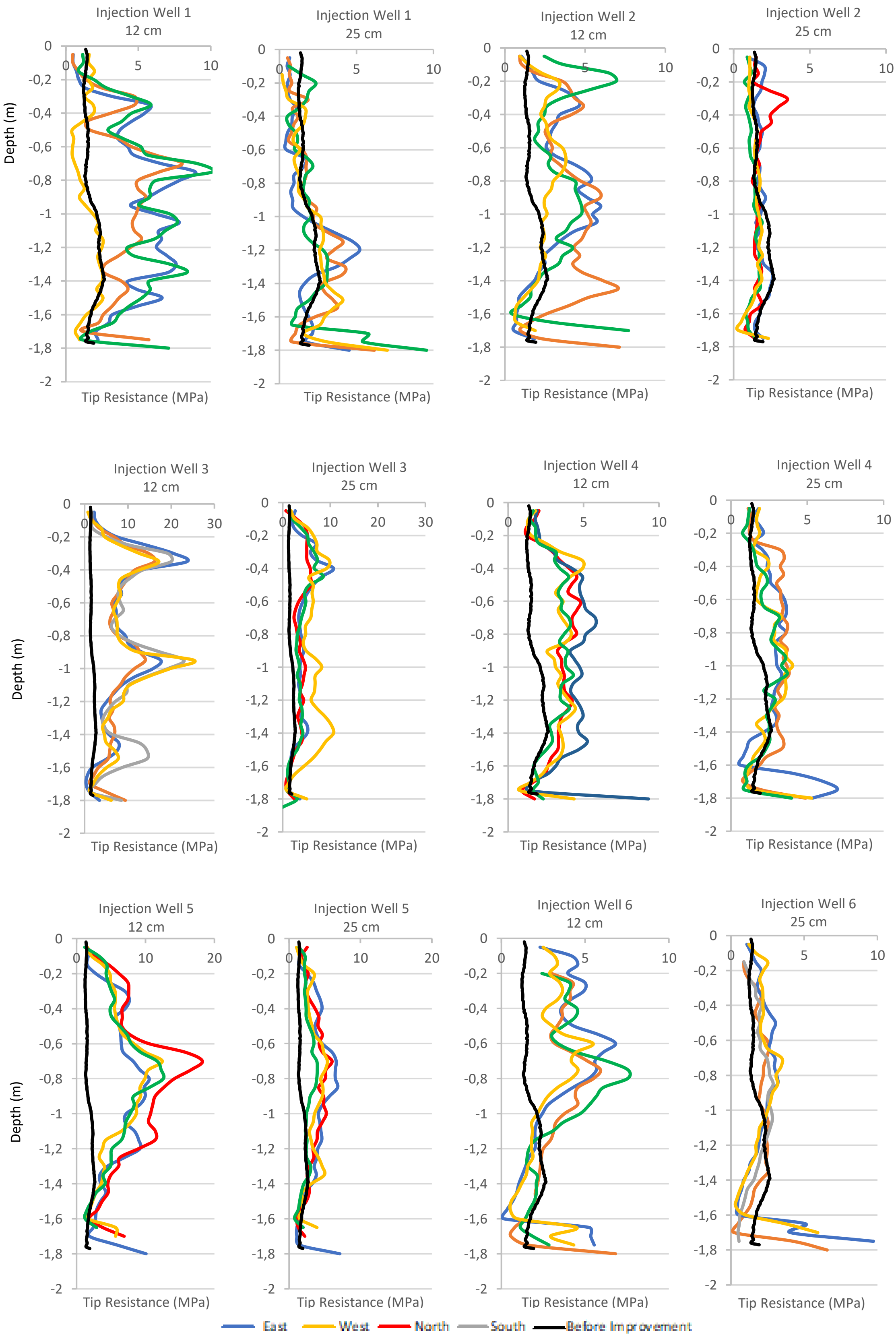

Figure 2. The tip resistance values for each injection well at 12cm and 25cm distances in four directions. (The black curve represents the tip resistances before soil improvement.)

3.6. Injection Well 6

The sleeves of the T.A.M. pipe were substituted with bike inner tubes. A reduced amount of solution, totalling 450 liters, was employed. Importantly, noticeable peaks weren't apparent down to a depth of 1 meter within the 12cm radius zone, indicating homogeneous treatment. Nevertheless, the graphical representation reveals that the final port exhibited ineffective functioning, which will be understood once the tube is extracted from the basin, as it appears that the injected fluid was washed away, leading to a lack of improvement in that area. Improvement was detected within a 25cm radius, achieving tip resistance values of 2-3 MPa, while within a 12cm radius, tip resistance values range from 3 to 5 MPa. Radial homogeneity was upheld.

4. CONCLUSIONS

This study investigated the application of the MICP technique for soil improvement under unsaturated conditions using a series of experiments involving six injection wells within a reinforced concrete basin filled with 0-4mm grain size sand. Notably, the observed soil improvement under various injection methods, revealed via a dynamic penetrometer campaign, validate the potential the MICP technique holds in improving substantially soil properties.

More precisely, a critical factor influencing the degree of homogeneity in soil improvement is the design of the injection tube and the spatial arrangement of the outlet ports along it. The results of Injection Wells 1, 2, and 3, clearly suggest that greater distances between ports lead to localized peak resistance values at the port levels. Conversely, decreasing these distances results in smaller and more evenly distributed peak values, yielding a more homogenous improvement profile throughout the soil depth.

The study also underscores the significance of the effective improvement diameter, which is influenced by injection parameters such as flow rate and pressure. The optimum pressure setting should be carefully determined, considering the spacing between ports on the injection tubes. Moreover, the application of additional CS cycles has substantially impacted tip resistance values, thus providing a feasible means to achieve higher strength. This highlights the importance of tailoring the injection parameters to the site's unique characteristics and project requirements to ensure optimal and effective soil improvement outcomes by optimizing the ratio of injected volume over achieved soil strength.

In summary, this study contributes valuable insights into the practical application of the MICP technique for the improvement of sands under unsaturated conditions. The results suggest the viability of MICP as a conventional soil improvement technique at the scale of conventional geotechnical works and provide guidelines for refining its implementation in terms of homogeneity, injection design, pressure optimization, and injection parameter determination. Further research and experimentation across diverse soil types will undoubtedly enhance the versatility and efficacy of MICP as a sustainable and innovative approach for soil enhancement as results suggest certain, targeted, refinements which are essential towards achieving homogenous improvements and towards extending the applicability of MICP to diverse soil types.

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