ELECTRIC CONDUCTIVITY FOR LABORATORY AND FIELD MONITORING OF INDUCED PARTIAL SATURATION (IPS) IN SANDS

A dissertation presented

by

Hadi Kazemiroodsari

to

Department of Civil and Environmental Engineering

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

in the field of

Civil Engineering

Northeastern University

Boston, Massachusetts

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ABSTRACT

Liquefaction is loss of shear strength in fully saturated loose sands caused by build-up of excess pore water pressure, during moderate to large earthquakes, leading to catastrophic failures of structures. Currently used liquefaction mitigation measures are often costly and cannot be applied at sites with existing structures. An innovative, practical, and cost effective liquefaction mitigation technique titled “Induced Partial Saturation” (IPS) was developed by researchers at Northeastern University. The IPS technique is based on injection of sodium percarbonate solution into fully saturated liquefaction susceptible sand. Sodium percarbonate dissolves in water and breaks down into sodium and carbonate ions and hydrogen peroxide which generates oxygen gas bubbles. Oxygen gas bubbles become trapped in sand pores and therefore decrease the degree of saturation of the sand, increase the compressibility of the soil, thus reduce its potential for liquefaction.

The implementation of IPS required the development and validation of a monitoring and evaluation technique that would help ensure that the sands are indeed partially saturated. This dissertation focuses on this aspect of the IPS research. The monitoring system developed was based on using electric conductivity fundamentals and probes to detect the transport of chemical solution, calculate degree of saturation of sand, and determine the final zone of partial saturation created by IPS. To understand the fundamentals of electric conductivity, laboratory bench-top tests were conducted using electric conductivity probes and small specimens of Ottawa sand. Bench-top tests were used to study rate of generation of gas bubbles due to reaction of sodium percarbonate solution in sand, and to confirm a theory based on which degree of saturation were calculated. In addition to bench-top tests, electric conductivity probes were used in a relatively large sand specimen prepared in a specially manufactured glass tank. IPS was implemented in the prepared specimen to validate the numerical simulation model and explore the use of conductivity probes to detect the transport of chemical solution, estimate
degree of saturation achieved due to injection of chemical solution, and evaluate final zone of partial saturation. The conductivity probe and the simulation results agreed well.

To study the effect of IPS on liquefaction response of the sand specimen, IPS was implemented in a large (2-story high) sand specimen prepared in the laminar box of NEES@Buffalo and then the specimen was subjected to harmonic shaking. Electric conductivity probes were used in the specimen treatment by controlling the duration and spacing of injection of the chemical solution, in monitoring the transport of chemical solution, in the estimation of zone of partial saturation achieved, and in the estimation of degree of saturation achieved due to implementation of IPS. The conductivity probes indicated partial saturation of the specimen. The shaking tests results confirmed the partial saturation state of the sand specimen.

In addition, to the laboratory works, electric conductivity probes were used in field implementation of IPS in a pilot test at the Wildlife Liquefaction Array (WLA) of NEES@UCSB site. The conductivity probes in the field test helped decide the optimum injection pressure, the injection tube spacing, and the degree of saturation that could be achieved in the field.

The various laboratory and field tests confirmed that electric conductivity and the probes devised and used can be invaluable in the implementation of IPS, by providing information regarding transport of the chemical solution, the spacing of injection tubes, duration of injection, and the zone and degree of partial saturation caused by IPS.
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Chapter 1

Introduction and Overview

This chapter presents an introduction of the research project on liquefaction mitigation, and an overview of the research reported in this dissertation, as part of the larger project.

1.1 Introduction

Large-scale liquefaction related damage to the built environment that was experienced during the 2011 Christchurch, New Zealand earthquake is a recent reminder that there is an urgent need to develop practical and cost-effective liquefaction mitigation measures. Liquefaction of saturated loose sands during an earthquake is associated with increase in pore water pressures as a result of ground shaking leading to loss of shearing strength of the sand. Liquefaction can lead to dramatic failures of buildings, bridges, earth dams, slopes, and other structures. Current liquefaction mitigation methods used in practice are often expensive and can only be implemented at sites where there are no structures.

Yegian et al., 2007 and Eseller-Bayat et al., 2012(a and b), proposed an innovative liquefaction mitigation measure that can be cost-effective and could be implemented under structures vulnerable to liquefaction-induced failures. The techniques is referred to Induced Partial Saturation (IPS), which involves generating small amount of minute gas bubbles within the pores of initially fully-saturated sand, thus increasing the compressibility of the pore water and reducing its tendency to generate excess pore water pressures, typically associated with significant intensity of ground shaking.

In 2011, The National Science Foundation (NSF) through the program George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) awarded Professors Yegian and Alshawabkeh of Northeastern University a research grant to understand the fundamentals of IPS and explore its potential benefits as a liquefaction mitigation measure when applied under large-scale laboratory and field conditions. The project collaborators
included: Professor S. Thevanayagam, from NEES@Buffalo, Professor Kenneth H. Stokoe, from NEES@UT, Dr. Jamison Steidl, from NEES@UCSB, and Professor Leslie Youd, formerly of Brigham Young University.

The title of the research project is: “Induced Partial Saturation Through Transport and Reactivity for Liquefaction Mitigation”. This technique involves injecting a chemical solution into a fully saturated liquefaction susceptible sand, and through transport of the solution and the chemical reactivity, oxygen gas bubbles are generated within the pores of the sand. The presence of the gas bubbles, reduce the degree of saturation, increases the compressibility of the pore water leading to reduction in the tendency of the excess pore pressure generation under ground excitation.

The chemical used for the generation of gas bubbles was sodium percarbonate (Na$_2$CO$_3$.1.5H$_2$O$_2$). The chemical dissolves in water and breaks down into sodium and carbonate ions, and hydrogen peroxide, which generates oxygen gas bubbles, as shown below in the chemical reaction.

\[
\begin{align*}
\text{Na}_2\text{CO}_3.1.5\text{H}_2\text{O}_2 & \xrightarrow{\text{in water}} 2\text{Na}^{+1} + \text{CO}_3^{2-} + 1.5\text{H}_2\text{O}_2 \\
1.5\text{H}_2\text{O}_2 & \xrightarrow{\text{in water}} 1.5\text{H}_2\text{O} + 0.75\text{O}_2
\end{align*}
\] (at the end of reaction)

(ideal conditions - 100% efficient)

Figure 1-1 depicts the process of IPS starting from mixing of the chemical, injection into the ground, and creating a partial saturation zone through transport and chemical reactivity. In this research, the application of IPS was divided into three main components.
Figure 1-1 Overall process of IPS. Black ovals highlight the IPS monitoring system, which was the focus of this dissertation.

The first component was developing and evaluating the efficiency of a delivery system consisting of: controlled mixing of the solution to obtain a desired concentration, installation of injection tubes, pumping of solution, reducing degree of saturation, and evaluating the benefits of partial saturation on liquefaction potential. A soon to be published dissertation by Fritz Nababan describes this component of the research. The second component was developing a numerical simulation model and a computer program to obtain the design parameters for IPS field implementation including: the design level of chemical concentration, pumping pressure, duration of injection, duration of wait period for the generation of oxygen, and predictions of the zone of partial saturation and the degree of saturation achieved. This component of the research was recently published in the dissertation of Seda Gokyer (2015). The third component of the IPS research entailed developing and implementing a monitoring system that assured the desired concentration of the chemical injected, and confirmed the duration of the injection and wait periods, zone of partial saturation, and the degree of saturation actually achieved within the treated zone.
The focus of this dissertation was on this component of the research, as shown in Figure 1-1.

1.2 Overview of this Dissertation

The IPS monitoring system that was described as the third main component of the research project was based on using electric conductivity to detect transport of the chemical, the rate of chemical reaction that generates gas, the generation of gas within voids of sand and consequent reduction in degree of saturation, and finally zone of partial saturation achieved. To explore the applicability and benefits of using electric conductivity, laboratory tests on small and large sand specimen, as well as a pilot field test were conducted.

Initially, bench-top laboratory tests were conducted using electric conductivity probes and small specimens of Ottawa sand to understand the fundamentals of electric conductivity as applied in IPS monitoring, and to determine rate of gas generation due to sodium percarbonate reaction. Also, tests were conducted to confirm the theory based upon which degree of saturation was calculated using electric conductivity tests results.

Following the bench-top laboratory tests, electric conductivity probes were used in a large sand specimen (91 cm x 13.5 cm x 55 cm) prepared in a especially manufactured glass tank. The purpose of the laboratory test in the glass tank was two folds: 1) to implement IPS and use the test results to validate the numerical simulation model (second main component of the research project), and 2) to further explore the use of conductivity probes in determining zone of partial saturation and reduction in degree of saturation due to injection of solution of sodium percarbonate; detection of gas bubble escape from the specimen; and evaluation of diffusion of the chemical ions due to differences in concentration within the specimen.

Further evaluation of the applicability of electric conductivity in monitoring IPS was made by instrumenting a very large sand specimen (5 m x 2.75 m x 5m)) prepared in the laminar box of NEES@Buffalo. The placement of electric conductivity probes in the laminar box was for the purpose of: 1) monitoring the IPS delivery system developed by Fritz Nababan, including concentration of chemical solution, duration of injection and
duration of wait time for gas generation; 2) estimation of the zones of partial saturation achieved and determining the required spacing of the injection tubes to treat the entire sand specimen; and 3) estimation of short- and long-term degree of saturation and detection of potential gas escape and diffusion of the chemical solution. The results of these tests helped validate the fundamental theories and interpretation of conductivity probe results in monitoring large-scale implementation of IPS.

The ability of electric conductivity probes to monitor field implementation of IPS was also explored in a pilot test conducted at the NEES@UCSB Wildlife Refuge site, in southern California. The field test using conductivity probes helped determine the optimum injection pressure, injection tube spacing, and size of zone of partial saturation. Based on these findings, the details of the final design of IPS implemented at the Wildlife Refuge were defined.

The conductivity probes used in all the laboratory and field tests described above were typical probes that are used in a laboratory. These probes were either inserted prior to the placement of the sand specimens or in the case of field applications, were installed in a pre-drilled borehole. A new field probe was manufactured to measure electric conductivity in the field, where the probe is pushed into the IPS treated sand. This technique avoids pre-drilling a borehole and disturbing the sand while installing the electric conductivity probe. Preliminary laboratory tests were conducted to evaluate if the field electric conductivity probe that is pushed into the sand can indeed accurately measure degree of saturation.

This dissertation presents the results of research on developing the theory and techniques of using electric conductivity to monitor application of IPS.

Chapter 2 presents an introduction of electric conductivity and its application in estimating degree of saturation. Chapter 3 presents descriptions of the various bench-top laboratory tests conducted to understand the rate of chemical reaction and to develop degree of saturation as a function of concentration of the chemical solution. Chapter 4 presents the results of electric conductivity probes used in the glass tank laboratory IPS tests. Chapter 5 presents the application of electric conductivity in the laminar box and
demonstrates how the probes are valuable tools in monitoring of implementation of IPS. **Chapter 6** summarizes the details of the pilot test performed at the NEES@UCSB Wildlife Refuge field site, where electric conductivity probes were helpful in determining the design parameters for field application of IPS. **Chapter 7** presents the results from the preliminary tests conducted in the laboratory using the new field probe to estimate degree of saturation using electric conductivity. **Chapter 8** summarizes the research results and presents conclusions and recommendations for future research.
Chapter 2

Electric Conductivity and Probes

2.1 Introduction

Successful implementation of IPS will require ability to monitor the chemical reaction that generates oxygen gas bubbles and to detect its effect on the degree of saturation in the treated sand. This dissertation is focused on developing techniques to achieve these goals. Electric conductivity is a common laboratory approach to detect the presence of ions in soils. Typically, a probe will measure the conductivity of a soil-fluid system between two electrodes. A dry soil will have low conductivity compared with a soil saturated with clean (ion-free) water. Similarly, the presence of ions in the pore fluid of a soil will increase the electric conductivity. In the case of IPS, presence of gas bubbles within the pores of a sand-fluid mixture will reduce the electric conductivity. In this dissertation these capabilities of electric conductivity probes were advanced and implemented to understand the fundamentals of the chemical reaction of sodium per carbonate that generates oxygen bubble, and to develop methods to monitor the rate of decrease in degree of saturation and to detect gas bubble generation or inadvertent gas bubble escape from the sand.

This chapter briefly introduces the theory behind using electric conductivity to detect presence of ions and to estimate degree of saturation. The chapter also includes details of the electric conductivity probe used in this research and demonstrates its ability to predict degree of saturation under application of IPS.
2.2 Electrical conductivity theory

In 1827, George Simon Ohm discovered that electric current between two points along a conductance relates directly to the potential difference between the points. Equation 2-1 represents Ohm’s law:

\[ V = I \times R \]  \hspace{1cm} (2-1)

In which, \( V \) is the potential in Volt, \( I \) is the current in Amp, and \( R \) is the resistance in ohm, \( \Omega \). The resistance of the conductance \( R \) is directly proportional to length, \( L \) and inversely proportional to cross section area, \( A \) (Equation 2-2).

\[ R = \rho \times \frac{L}{A} \]  \hspace{1cm} (2-2)

In Equation 2-2, \( \rho \) is a constant which is the property of the conductance and is called electrical resistivity. Resistivity has the unit of ohm m (\( \Omega \cdot m \)).

Electrical conductivity, \( \sigma \) has unit of Siemens per meter (S/m) and is defined as reciprocal of electrical resistivity, \( \rho \) (Equation 2-3).

\[ \sigma = \frac{1}{\rho} \]  \hspace{1cm} (2-3)

By combining Equations 2-2 and 2-3, Equation 2-4 is derived.

\[ \sigma = \frac{L}{R \times A} \]  \hspace{1cm} (2-4)

Electrical conductivity, \( \sigma \) is the property of the material, which represents the ability to conduct an electric current. In soils, the value of electrical conductivity depends on properties of the soil such as, porosity, degree of saturation, mineralogy including shape and size of particles, soil structure including fabric and cementation and conductivity of pore fluid (Mitchell, James Kenneth, and Kenichi Soga, 1976).

By combining Equations (2-1) and (2-4), Ohm’s law can be presented as in Equation 2-5:
Equation 2-5 represents the flow of electricity through a conductance, be it a wire or a soil fluid mixture. \( \frac{V}{L} \) represents the electrical gradient between the two electrodes, and \( A \) represents the general area of the electric field.

2.3 Application of electric conductivity concept in soil

As mentioned in Section 2.2, electric conductivity can be used in a sand-fluid mixture in the case of application of IPS.

![Principle of electric conductivity meter in soil](image)

Electric conductivity is determined by measuring the resistance of a soil-fluid mixture material between two electrodes (Bockris, J. O'M.; Reddy, A.K.N; Gamboa-Aldeco, M. (1998)). By applying a given voltage \( V \) to the electrodes, which are placed inside a medium, current \( I \) is measured. From voltage and current measurements, electric resistance \( R \) is calculated. The current can be direct current (DC) or alternating (AC) current with small frequency. It is recommended to use alternating current (AC) in order to prevent electrolysis. Electric conductivity could be determined from Equation 2-4 by multiplying \( \frac{1}{R} \) to the constant \( \frac{I}{A} \) (Cell constant), which depends on the distance between electrodes and
area which represents the electric field. The Cell-constant depends on the distance and sizes of the electrodes and is established for each conductivity meter by using a calibration fluid of known conductivity. Calibration involves placing a conductivity probe in the calibration fluid and adjusting the reading of the meter to read the conductivity of the calibration fluid. This way the probe is calibrated for the $\frac{L}{A}$ (Cell constant) factor.

2.4 Application of electric conductivity in IPS

IPS involves transporting a low concentration of sodium per carbonate through a fully saturated sand and through chemical reaction, oxygen bubbles are generated within the pores of the sand, thus reducing its degree of saturation. There are many benefits of using an electric conductivity probe in such an application. The general concept of the functionality of a conductivity probe is explained in this section.

2.4.1 Detecting arrival and concentration of IPS chemical

Electric current is a flow of electric charge, which in electric circuits this charge is carried by electrons, and in electrolytes by ions (Anthony C. Fischer-Cripps, 2004). Sodium per carbonate dissolves in water and breaks down into sodium and carbonate ions and hydrogen peroxide. Presence of sodium and carbonate ions in sodium per carbonate solution leads to larger electric conductivity value compared to pure water. An electric conductivity probe placed in a sand specimen will detect the arrival of these ions as the solution of sodium per carbonate is injected and transported through the sand. Therefore, probes located at various distances from an injection well or tube, can help determine the arrival and concentration of the solution that has reached at a probe and the readings from various probes can define the general zone of IPS treatment of the sand using sodium per carbonate.

2.4.2 Estimating degree of saturation and rate of generation of gas bubbles

The reaction of sodium per carbonate with water results in production of hydrogen peroxide, which is the source of oxygen gas bubble generated within the pores of an IPS
treated sand. Because of the minute sizes of these gas bubbles, they are trapped within the pores of the sand and cause a reduction in the electric conductivity of the sand-fluid mixture from what it was before the reaction started. The rate of decrease in electric conductivity represents the rate of generation of bubbles.

The change in electric conductivity due to bubble generation can be used to estimate the change in the degree of saturation of the sand. The relation between electric conductivity and degree of saturation of soil has been presented by Archie in 1942.

### 2.4.2.1 Archie’s law

Running experiments on clean sand, Archie (1942) expressed that the resistivity of sand is directly proportional to the pore brine. Archie defined Equation 2-6 as a linear relation between resistivity of sand and resistivity of brine.

\[ F = \frac{\rho}{\rho_w} \]  

(2-6)

Where, \( \rho \) and \( \rho_w \) represent resistivity of sand and brine, respectively, and \( F \) is a formation factor. Archie also provided a relationship between formation factor (\( F \)) and porosity of clean sand, as well as degree of saturation of sand (Equation 2-7).

\[ F = \frac{\rho}{\rho_w} = a \times \varphi^{-m} \times S^{-n} \]  

(2-7)

In which, \( \varphi \) and \( S \) are porosity and degree of saturation of sand, respectively, \( a \), \( m \), and \( n \) are soil factors. \( a \) is called tortuosity factor and is meant for correction for compaction pore structure and grain size. The value of \( a \) is typically between 0.5-1.5 (Winsauer et al. 1952). \( m \) is called cementation exponent and can vary from 1.3 for loose sands to 2 for highly cemented sandstones (Mitchell, James Kenneth, and Kenichi Soga, 1976). \( n \) is saturation exponent determined experimentally. Archie suggested \( n=2 \) for clean sands.

As was shown in Equation 2-3, electric conductivity \( \sigma \) is defined as reciprocal of resistivity \( \rho \). Therefore, Equation 2-8 can be driven from Equation 2-7.

\[ \sigma = \frac{1}{a} \times \sigma_w \times \varphi^m \times S^n \]  

(2-8)
In Equation 2-8, $\sigma$ and $\sigma_w$ represent electric conductivity of sand and electric conductivity of brine, respectively. Equation 2-8 can be used in IPS application to calculate degree of saturation of sand specimen.

To demonstrate the application of Archi’s law in IPS application, a typical electric conductivity plot is sketched in Figure 2-2.

![Figure 2-2 Typical electric conductivity plot showing arrival of the sodium per carbonate solution and generation effect of gas bubbles](image)

The plot starts with point that represents the electric conductivity of fully saturated sand ($\sigma_i$). When sodium percarbonate solution arrives within the sand pores presence of sodium and carbonate ions leads to increase in electric conductivity (from $\sigma_i$ to $\sigma_p$). This increase continues until the maximum concentration of sodium percarbonate is achieved ($\sigma_p$). The decrease in electric conductivity value (from point $\sigma_p$ to point $\sigma_R$) represents the generation of gas bubbles. It is noted that while the solution of sodium percarbonate is transported through the sand, there is a very slow rate of gas generation. Therefore, during the time from $\sigma_i$ to $\sigma_p$, the rise in electric conductivity has the effect of gas generation, which would reduce electric conductivity. It is assumed that the increase in electric conductivity due to ion arrival is relatively far larger than what the decrease would be due to small amount of gas generation during the short period of time. This assumption was later proven to be valid using laboratory tests of IPS treated sands, described in Chapter 4. Therefore, in the calculations of degree of saturation $S$, it is assumed that $S = 100\%$ at the
time of peak electric conductivity, \((\sigma_p)\). Another assumption is made that the Tortuosity factor, cementation exponent, porosity and saturation exponent don’t change significantly during the generation of bubbles (from point \(\sigma_p\) to point \(\sigma_R\)), an assumption also validated using laboratory tests of IPS, described in Chapter 3.

By applying Equation 2-8 at any time during gas generation, between \(\sigma_p\) and \(\sigma_R\) the degree of saturation of that specific time can be calculated. Equation 2-9 gives the expression for the final degree of saturation \(S_R\) achieved at point \(\sigma_R\). Equation 2-9, assumes that the saturation exponent, \(n=2\). This assumption also was validated using laboratory test results Described in Chapter 3.

\[
S_R = \frac{\sigma_R}{\sigma_p}^{\frac{1}{2}}
\]  

(2-9)

2.5 Milwaukee electric conductivity probe and meter

The electric conductivity probes and meters which were used in this research were SE502 and MW302 respectively, manufactured by Milwaukee Instruments. The calibration fluid is an international calibration solution with electric conductivity value of 1413\(\mu\)S/cm. The calibration of a probe entails immersing the electrodes in the calibration fluid without touching the fluid container. The reading of the meter is then adjusted be to an electric conductivity value of 1413\(\mu\)S/cm, using a small screw located on the meter. Figure 2-3 shows the electric conductivity probe (SE502), meter (MW302) and calibration solution (1413\(\mu\)S/cm), used in this research.
Figure 2-3 a) Milwaukee electric conductivity meter and probe b) calibration solution

Table 2-1 presents MW302 electric conductivity meter specifications obtained from: (http://www.milwaukeeinstruments.com/site/products/products/standardportable-meters/83-products-g-standard-portable-meters-g-mw302).

### Table 2-1 MW320 meter specifications

<table>
<thead>
<tr>
<th>MW320 Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range *</td>
<td>0.0-10.0 mS/cm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 mS/cm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±2% Full Scale</td>
</tr>
<tr>
<td>Temperature compensation</td>
<td>Automatic, from 5 to 50°C</td>
</tr>
<tr>
<td>Battery Type</td>
<td>9v</td>
</tr>
<tr>
<td>Dimension</td>
<td>145x80x40 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>220</td>
</tr>
</tbody>
</table>

*The MW302 has the ability to read within the range of 0.0-20.0 mS/cm but within the range of 10.0-20.0 mS/cm meter loses its accuracy.

#### 2.5.1 Accuracy check of SE502 probe and MW320 meter

As Milwaukee electric conductivity meter (MW 302) has accuracy of ± 0.2 mS/cm, to ensure that the quality of the meter is acceptable in our research, test results of the MW
302 meter along with its probe, SE520, were compared with a more accurate electric conductivity meter and probe (Orion 4 star -Thermo Scientific).

Table 2-2 presents the specifications of the Orion 4 star –Thermo Scientific probe and meter.

<table>
<thead>
<tr>
<th>Orion 4 start - Thermo Scientific Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
</tr>
<tr>
<td>0.000-3000 mS/cm</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
</tr>
<tr>
<td>Down to 0.001µS/cm</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
</tr>
<tr>
<td>0.5%,±1% digit or 0.01 µS/cm , Whichever is greater</td>
</tr>
</tbody>
</table>

Figure 2-4 shows the Orion 4 star-Thermo Scientific electric conductivity meter with its probe.

Figure 2-4 Orion 4 star-Thermo Scientific electric conductivity meter and probe

A bench-top laboratory test with Ottawa sand was conducted to compare Milwaukee and Thermo Scientific electric conductivity probe and meters. Both the Milwaukee and the Thermo Scientific probes were calibrated prior to the tests. The sand specimen was prepared by first mixing a 1% by weight of sodium percarbonate in water and placing it in a beaker. Then, both Milwaukee and Thermo scientific probes were placed within the beaker symmetrically from the center of the beaker. A certain amount of dry Ottawa sand (C778) was then poured slowly in the beaker while electric conductivity probes where kept at their locations. After completing the sand placement, the amount of solution left on top
of the specimen above the sand level was measured. Figure 2-5 shows the bench top experiment set up.

Figure 2-5 Bench top experiment set up to compare Milwaukee and Thermo Scientific electric conductivity meters and probes

After the sand specimen was prepared, the electric conductivity readings from both Milwaukee and Thermo Scientific meters were recorded for 250 minutes. The results of electric conductivity are shown in Figure 2-6 (a).

Figure 2-6 (a) Comparison of Milwaukee and Thermo Scientific electric conductivity readings, (b) Degree of saturation based on Archi’s law compared with based on volume calculations
The initial readings of the meters represent the electric conductivity of the sand with 1% sodium per carbonate solution in the pores. When gas bubbles were generated and became trapped in the sand pores, the value of electric conductivity dropped, as shown in Figure 2-6 (a), because of the reduction in the amount of conductive fluid expelled by the gas bubbles. The conductivity readings of the two probes and meters, generally were very comparable and confirm that the Milwaukee probe and meter, which are much cheaper and readily available than the Thermo Scientific ones, are acceptable. Only when the values of electric conductivity are smaller than 1.5 (mS/cm), the Milwaukee probe slightly underestimates the electric conductivity, because of its lower sensitivity.

Using the readings of electric conductivity and Equation 2-9, degrees of saturation were calculated from both types of probes. Figure 2-6 (b) shows the calculated degrees of saturation S, as a function of time. As expected, the S results tend to follow the same trends as the electric conductivity readings. Again, the Milwaukee probe is able to give degree of saturation very similar to the values obtained using the Thermo Scientific probe. The final degree of saturation from the Milwaukee probe is about 54%, and compares well with 60% obtained by the Thermo Scientific.

An additional set of calculations were made to estimate the degree of saturation to ensure that both probes and meters indeed yield reliable values of degree of saturation. It is recalled that the value of the saturation exponent, n was assumed to be 2 (as recommended by Archie), which resulted in the square root function of Equation 2-9 for degree of saturation. The approach for this additional set of calculations is based on measurement of volume of water expelled by the gas generated within the sand pores and use of phase relationships of soil mechanics. Figure 2-7 shows the process of sand specimen preparation and measurement of volumes.
During gas generation phase of the laboratory test described earlier in this section, water accumulated on top of the sand specimen, as the trapped gas displaced the pore water. This volume of water was measured and assumed to be the same as the volume of trapped gas, $V_a$. The volume of the sand solid, $V_s$ was calculated using Equation 2-10.

By knowing the mass of dry sand used in the specimen ($m_s$), specific gravity of Ottawa sand ($G_s$) equal to 2.65 and assuming unit weight of water ($\gamma_w$) equal to 1 gr/cm$^3$, volume of sand used in the specimen ($V_s$) can be calculated from equation 2-10.

\[
V_s = \frac{m_s}{G_s \times \gamma_w} \tag{2-10}
\]

In which, $m_s$ is the mass of dry sand used in the specimen, $G_s$ is the specific gravity of Ottawa sand equal to 2.65, and $\gamma_w$ is the unit weight of water equal to 1 gr/cm$^3$.

The volume of voids ($V_v$) can be calculated from Equation 2-11, where $V_T$ is the measured total volume of the specimen.

\[
V_v = V_T - V_s \tag{2-11}
\]

Finally, the degree of saturation of the specimen $S$, can be calculated from Equation 2-12.

\[
S = \frac{(V_v - V_a)}{V_v} \tag{2-12}
\]
Figure 2-6 (b) includes the results of degree of saturation calculated using volume measurements and phase relationships. The results from volume calculations compare well with those obtained using the electric conductivity probes, considering the difficulties in measuring small volumes in the laboratory experiment.

Degree of saturation calculated based on Archi’s law, using Milwaukee and Thermo Scientific conductivity kits can be compared with degree of saturation calculated based on volume calculation.

In summary, the experimental test results shown in Figure 2-6 confirm that the Milwaukee probe readings of electric conductivity together with Equation 2-9, which assumes that the saturation exponent is $n = 2$ can indeed provide reliable and reasonably accurate rate of decrease in degree of saturation during gas generation, as well as final degree of saturation when gas generation is completed.

### 2.5.2 Extending cable of Milwaukee electric conductivity probe

SE 520 electric conductivity probe which is manufactured by Milwaukee Instrument comes with 1 meter long cable. These probes were used in small-scale laboratory specimens without extending the factory connected cables. The probes were also used in large-scale laboratory and field applications, which necessitated the extending of the cables from 1 meter to as long as 10 to 15 meters. It was of interest to know, if extending the cables of the Milwaukee probes with new connectors would have adverse effect on the electric conductivity readings. Figure 2-8 shows SE520 Milwaukee probe with a long extended cable.
A bench top experiment similar to the one described in Section 2.5.1 was performed to compare the readings of SE520 Milwaukee probe with factory connected 1 meter cable with the readings of SE520 Milwaukee probe with a long extended cable. Figure 2-9 shows a comparison of the measured electric conductivity using the probes with short- and long-cables.

The plots shown in Figure 2-9 confirm that extending the cables have no appreciable effect on the measured electric conductivity. The erratic readings after 220 minutes are due to escape of gas bubbles from the small specimen probably associated with small vibrations of the sample or the large amount of gas bubbles formed in a small sand specimen, and therefore is irrelevant for the purpose of this test.
Chapter 3

Bench-Top Laboratory Tests Using Electric Conductivity
Probe to Study Rate of Gas Generation and Degree of
Saturation in Sand

3.1 Overview

Bench-top laboratory experiments were conducted on small specimens of Ottawa sand partially saturated using varying concentrations of sodium per carbonate solution. Measurements of electric conductivity were made to: 1) verify the procedure for calculating the degree of saturation using electric conductivity data; 2) determine the rate of gas generation; and 3) determine if the void ratio of a specimen has an effect on the reduction in degree of saturation induced by gas generation.

This chapter describes the details of the laboratory tests conducted, and presents the electric conductivity data to evaluate each of the three goals stated above.

3.2 Verification of the procedure for calculating degree of saturation

One of the main purposes of using electric conductivity probes in this research is to monitor the generation of gas bubbles in a sand, leading to reduction in electric conductivity, and hence reduction in degree of saturation. The calculation of degree of saturation induced by IPS is based on Archie’s law and a number of assumptions. Details of the application of Archie’s law and the assumptions made were presented in Chapter 2. Equation 2-9 from Chapter 2 is replicated herein as Equation 3-1, which is used to calculate degree of saturation, $S_R$.

$$S_R = \frac{\sigma_R}{\sqrt{\sigma_p}}$$ (3-1)
Figure 3-1 shows a typical electric conductivity plot, in which \( \sigma_p \) is the electric conductivity of a sand specimen saturated with certain concentration of sodium percarbonate solution, \( \sigma_R \) is the electric conductivity at the end of gas generation within the pores of the sand specimen, and \( S_R \) is the degree of saturation at the end of gas generation. Equation 3-1 can be applied using electric conductivity reading at any time during gas generation to calculate the degree of saturation at that time.

![Electric Conductivity Plot](image)

Figure 3-1 Typical electric conductivity plot from bench-top test

To verify the validity of Equation 3-1, a number of tests were conducted on small specimens of partially saturated sand. The specimen preparation was as follows:

Step 1: An electric conductivity probe was placed in the center of a beaker.

Step 2: A solution of sodium percarbonate with a desired concentration was prepared using magnetic stirrers, as shown in Figure 3-2, and poured into the beaker that had the conductivity probe. The volume of the solution was recorded.

Step 3: Dry Ottawa sand (Figure 3-3) was rained into the beaker creating a fully saturated sand specimen (Figure 3-4). The weight of the dry sand used was recorded.
Step 4: Electric conductivity readings (Figure 3-5) and the volume of solution accumulating on top of the specimen were recorded at various time intervals.

Sodium Per carbonate:
\[ \text{Na}_2 \text{CO}_3 \cdot 1.5 \text{H}_2 \text{O}_2 \]

\[ \text{Na}_2 \text{CO}_3 \cdot 1.5 \text{H}_2 \text{O}_2 \quad \text{in water} \rightarrow 2\text{Na}^{+1} + \text{CO}_3^{2-} + 1.5\text{H}_2 \text{O}_2 \]

\[ 1.5\text{H}_2 \text{O}_2 \quad \text{in water} \rightarrow 1.5\text{H}_2 \text{O} + 0.75\text{O}_2 \]

Figure 3-2 Preparation of Sodium per carbonate solution using magnetic stirrer

Figure 3-3 Grain size distribution of Ottawa sand (ASTM C778)

Figure 3-4 Prepared specimen of bench-top test
Figure 3-5 presents the measured electric conductivity readings from sand specimens partially saturated with chemical solution having concentrations of 0.5%, 1%, 1.2%, 1.5% and 4%. The plots on the left of Figure 3-5 show the electric conductivity data. All five specimens had generally similar void ratios (0.62 – 0.69). As expected, the higher the concentration of the solution, the larger was the initial reading of electric conductivity. Also, the higher the concentration, the shorter was the time to the end of gas generation. Which means the rate of the reaction depends on the concentration of the solution. Further discussions on this will be presented in Section 3-3.
Figure 3-5 Electric conductivity (on the left) and degree of saturation (on the right) for various concentrations of chemical solution.
It is also noted from the electric conductivity data of Figure 3-5 that when the concentration of the chemical solution was high (> 1.2%), gas bubbles tended to escape from the specimens. The larger the concentration, the more bubbles escaped. This bubble escape is attributed to the ease of gas escaping along the smooth housing of the electric conductivity probe. Thus, most likely this situation was local to the probe and hence had pronounced impact on the probe’s reading.

Using the electric conductivity data of Figure 3-5 and Equation 3-1 the degree of saturation as a function of time were calculated for each of the five sand specimens. The results are presented in the plots shown on the right side of Figure 3-5. The reduction in degree of saturation as a result of gas generation can be observed. The calculations were made till the time prior to gas bubble escape giving the general degree of saturation of the specimens at that time. As expected, the plots indicate that the higher the concentration of the solution, the lower is the final degree of saturation. Also, the higher the concentration, the faster is the time to final degree of saturation. These observations expectedly are consistent with those made based on the raw data of electric conductivity.

To verify that the procedure for the calculation of degree of saturation is valid, the measurements of the mass of the dry sand, the initial volume of solution, volume of the specimen, as well as volume of the solution accumulated at the surface of each specimen as a result of gas generation, were used and the degree of saturation were calculated, using equations of phase relations. The results of these calculations of degree of saturation are plotted on the right side of Figure 3-5. The plots are labeled “based on volume calculations”.

The comparisons made between the degree of saturation plots based on electric conductivity and based on volume calculations lead to the following observations:

1- The two methods yield reasonably similar degree of saturation for during and end of gas generation periods.

2- In general, the degree of saturation based on electric conductivity is slightly larger than based on volume calculations. This can be due to a number of factors: 1- inaccuracy in measuring small changes in the volume of the expelled water due to
gas generation, 2- potential gas escape at the conductivity probe location during the gas generation period, and 3- inaccuracy of Equation 3-1 for the calculation of degree of saturation.

3- Volume calculations do not indicate significant bubble escape, which confirms that gas escape most likely was localized around and at the tip of the conductivity probe.

4- Overall, the plots of degree of saturation based on volume calculations confirm that electric conductivity readings together with Equation 3-1 can provide reliable estimates of degree of saturation of sands treated by IPS.

The bench-top tests also provided estimates of the final degree of saturation as a function of concentration of the chemical solution. Figure 3-6 presents the results of final degree of saturation.

![Figure 3-6 Final degree of saturation for concentrations between 0.5% and 4%](image)

The results summarized in Figure 3-6 indicate that for 0.5% concentration of the chemical solution a degree of saturation as low as 75% can be achieved in laboratory specimens. For a concentration of 1.5%, at a minimum 50% degree of saturation can be achieved. It is noted that beyond a concentration of about 1.5%, the degree of saturation does not decrease further. This can be attributed to earlier observations by Eseller-Bayat et al. (2014) that when the degree of saturation is reduced below about 40% by introducing gas bubbles matric suction is developed, and the gas bubbles are no longer in equilibrium...
with hydrostatic water pressure. Increase in moles of gas because of large concentration of chemical solution will then increase the pressure of the trapped gas, which has a constant volume limited by the void space of the sand. This may also be the reason for gas escape especially when the concentration is high (>1.5%) and there is an easy vertical path, such as the presence of a conductivity probe. In practical applications of IPS in the field, it is anticipated that the concentration of the chemical solution will typically be less than 1%, providing a reduction in degree of saturation to about 60%.

In summary, Figures 3-5 and 3-6 show that the degrees of saturation calculated using electric conductivity and Equation 3-1 are very comparable with those obtained using volume calculations. These comparisons confirm that the procedure developed for the calculation of degree of saturation based on electric conductivity can provide reasonable and reliable estimates of S.

3.3 Determine rate of gas generation

In numerical modelling of IPS, using the computer program (SUTRA-Bubble) developed by Seda Gokyer (2015), gas generation is related to decomposition of solute. For example, decomposition of m moles of solute results in generation of n moles of gas bubbles. Typically, decomposition of a chemical follows an exponential rate expression. Figure 3-7 presents an exponential decomposition of solute resulting in gas bubble generation that was assumed by Gokyer.

![Figure 3-7 Schematic for exponential decomposition of solute resulting in gas bubble generation](image-url)
Equation 3-2 represents the decomposition of solute:

\[ C(t) = C_0 \times \exp(-rt) \quad (3-2) \]

In Equation 3-2, \( C(t) \) is the concentration of the solute at time \( t \), \( C_0 \) is the initial concentration of the solute and \( r \) is a rate parameter.

Differentiating Equation 3-2, the rate of decomposition of the solute is given by Equation 3-3.

\[ \frac{\Delta C(t)}{\Delta t} = -r\, (C_0) \times \exp(-rt) = -rC(t) \quad (3-3) \]

The computer program SUTRA-Bubble uses Equation 3-3 to estimate moles of gas bubble generated over time. More details about the decomposition of hydrogen peroxide (the source of oxygen gas generation) and the rate parameter are presented in the dissertation of Seda Gokyer.

To determine the rate parameter \( r \), bench-top tests were run on sand specimens partially saturated by sodium percarbonate solution introduced into the specimens. An electric conductivity probe was used to monitor and record the rate of gas generation, as was described in Section 3-2.

As it was explained earlier, the reduction in electric conductivity (\( \sigma_p \) to \( \sigma_R \) in Figure 3-1) is related to gas bubble generation due the decay of hydrogen peroxide. Therefore, an exponential trend similar to the trend of decay of hydrogen peroxide is expected to be observed in electric conductivity plots over time. This exponential trend can be formulated as in Equation 3-4:

\[ \sigma(t) = (\sigma_p - \sigma_R) \times \exp(-rt) + \sigma_R \]

or,

\[ \sigma(t) - \sigma_R = (\sigma_p - \sigma_R) \times \exp(-rt) \quad (3-4) \]
In Equation 3-4, $\sigma (t)$ represents electric conductivity at time $t$ and $\sigma_p$ and $\sigma_R$ are the initial and final electric conductivities, as were shown in Figure 3-1.

As reduction in electric conductivity is due to decay of hydrogen peroxide (the solute) generating oxygen gas, by comparing Equations 3-2 and 3-4 it can be stated that $(\sigma_p - \sigma_R)$ is proportional to initial concentration of the solute and can be considered to be $(C_0)$, and $(\sigma (t) - \sigma_R)$ represents the remaining concentration of hydrogen peroxide at time $t$ and is proportional to $C (t)$. Therefore, Equations 3-2 and 3-4 essentially define the same trend. Equation 3-2 describes the decay of hydrogen peroxide (or rate of generation of gas bubbles), and Equation 3-4 defines the reduction in electric conductivity (again describing the rate of generation of gas bubbles).

The electric conductivity data shown in Figure 3-5 obtained from the bench-top tests were utilized to estimate the rate parameter $r$ of Equations 3-2 and 3-4. Best-fit lines were established using the set of data (up to the point of start of gas bubble escape) for each of the five concentrations. Figure 3-8 represents the electric conductivity data and the fitted lines for the different concentrations.
Figure 3-8 Electric conductivity data and fitted lines based on Equation 3-4 for concentrations of: 0.5%, 1%, 1.2%, 1.5%, and 4%

The values of the rate parameter ($r$) shown in the Figure 3-8 correspond to the largest coefficient of determination ($R^2$).

Table 3-1 summarizes the rate parameters and the coefficients of determination ($R^2$), which are close to 1, signifying a good fit of the lines with the data.
Table 3-1 Rate parameter and coefficient of determination

<table>
<thead>
<tr>
<th>Concentration (%)</th>
<th>Exponential Coefficient, ( r ) (1/sec)</th>
<th>Coefficient of Determination, ( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.0000833</td>
<td>0.96</td>
</tr>
<tr>
<td>1</td>
<td>0.000133</td>
<td>0.99</td>
</tr>
<tr>
<td>1.2</td>
<td>0.00018</td>
<td>0.96</td>
</tr>
<tr>
<td>1.5</td>
<td>0.00022</td>
<td>0.98</td>
</tr>
<tr>
<td>4</td>
<td>0.00053</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Figure 3-9 shows the rate parameter plotted as a function of concentration.

![Graph showing rate parameter versus concentration](image)

Figure 3-9 Rate parameter versus concentration

Figure 3-9 shows that the rate parameter increases approximately linearly with concentration. Increase in the rate parameter with concentration implies that the chemical reaction and generation of oxygen is faster when the concentration is higher. This has practical implications when it comes to field implementation of IPS. When the concentration of the chemical solution is high, the delivery system of the solution into the ground should be rapid; otherwise the fast rate of large amount of gas generated at the tip of an injection tube can reduce the permeability of the soil drastically, thus hindering further injection of the solution into the ground. For rapid injection of a high concentration of solution, higher injection pressures may be required.
To demonstrate the important effect of concentration on the rate parameter, Equation 3-4 was normalized as shown in Equation 3-5.

\[
\frac{(\sigma(t) - \sigma_R)}{(\sigma_p - \sigma_R)} = \exp(-rt)
\]  

Equation 3-5 represents the remaining concentration of hydrogen peroxide normalized to initial concentration of hydrogen peroxide. Figure 3-10 (a) shows the normalized electrical conductivity data. Figure 3-10 (b) shows the normalized fitted curves using the r values shown in Table 3-1. The data and the fitted lines clearly show that the higher the concentration, the faster is the chemical reaction. A solution with 0.5% concentration will take longer than 500 minutes (8 hrs.) to complete the reaction, while a solution with 4% concentration will complete its reaction in about 200 minutes (3.3 hrs.).
Figure 3-10 Effect of concentration of chemical on the rate of reaction and gas generation: (a) normalized electric conductivity data, (b) normalized fitted lines using r values from Table 3-1

3.4 Effect of void ratio on degree of saturation

The calculation of degree of saturation is made using Equation 3-1. The theory behind this equation was introduced and discussed in Chapter 2. According to Archie, electric conductivity $\sigma$ is related to conductivity of the solution $\sigma_w$, porosity $\phi$, and degree of saturation $S$. Equation 2-8 from Chapter 2 is replicated herein as Equation 3-6.

$$\sigma = \frac{1}{a} \times \sigma_w \times \phi^m \times S^n$$ (3-6)

The parameters $a$, $m$, and $n$ are suggested by Archie to be constant. Equation 3-1 provides an estimate of degree of saturations. This equation was arrived at by dividing electric conductivity value at a particular time with the peak electric conductivity associated with the full concentration of the solute. The square-root function in Equation 3-1 is the result of assuming $n=2$ as suggested by Archie, and verified with bench-top tests that were described in Section 3.2. Theoretically, electric conductivity of the solution $\sigma_w$ and porosity $\phi$ drop out of this ratio because they as well as the parameter $m$ are assumed to be constant. These assumptions are tested further.
In the implementation of IPS, a certain concentration of solution is injected until the full concentration is achieved at a probe location. The electric conductivity of the solution is then $\sigma_w$ and remains constant, except for a small effect of diffusion. Another assumption made is that during the injection of the solution, the injection pressures are controlled to ensure that there will be no blow-out conditions and therefore, there will be no change in the porosity $\varphi$ of the natural soil or of a laboratory sand specimen. The third and last assumption is that the power $m$ of the porosity factor is constant. If this parameter were not constant but dependent on porosity, then Equation 3-1 would be at best inaccurate, or at worst incorrect.

To further validate Equation 3-1 a number of bench-top tests were conducted on sand specimens with different void ratios and partially saturated using a solution with 1% concentration.

Figure 3-11 presents the electric conductivity data and the calculated degrees of saturation for void ratios of: 0.55, 0.62, 0.69, and 0.78.
Figure 3-11 Electric conductivity and degree of saturation for void ratios of: 0.55, 0.62, 0.69, and 0.78
Figure 3-12 presents summary plots of degree of saturation for different void ratios. The results clearly confirm that the procedure for calculating degree of saturation, $S$ using Equations 2-9 or 3-1 is valid, and the void ratio of the natural soil or the sand specimen makes inappreciable difference on $S$.

![Figure 3-12 Degree of saturation for different void ratios, and 1% concentration.](image)

### 3.5 Summary and Conclusion

Bench-top tests were conducted on sand specimens, partially saturated using solution of sodium percarbonate with varying concentrations. The solution generated oxygen gas bubbles in the pores of the sand, thus reducing the degree of saturation. Measurements of electric conductivity were made and the results were used to calculate the degree of saturation as a function of time, using a procedure based on Archie’s law. Based on measured mass of the sand and volumes of the specimen and solution, the degrees of saturation of the various specimens were also calculated using equations of phase relations. The degrees of saturation based on electric conductivity were compared with those based on volume calculations and phase relations.

It is concluded that the procedure developed for the calculation of degree of saturation based on electric conductivity can yield reliable and convenient estimates of degree of saturation in the application of IPS.
The bench-top test results of electric conductivity were also used to investigate the rate of generation of oxygen gas using sodium percarbonate. Analysis of the data was made assuming the rate of increase in gas bubbles, or the rate of decrease in degree of saturation follows an exponential function defined with a rate parameter $r$.

It is concluded that the rate of decay of the chemical and generation of gas indeed follows approximately an exponential function. The rate parameter, $r$ depends on the concentration of the solution used to generate gas in the pores of the sand specimens. The higher the concentration, the faster is the reaction and hence the reduction in degree of saturation.

Additional bench-top tests were conducted on specimens of sand with varying void ratios. The specimens were partially saturated using a 1% concentration of sodium percarbonate. The purpose of the tests was to determine if void ratio of the specimens had an effect on the procedure for the calculation of degree of saturations based on electric conductivity.

It is concluded that void ratio, as long as it remains constant during IPS injection, has no appreciable effect on the calculated degree of saturation.
Chapter 4

Use of Electric Conductivity Probes for Monitoring IPS in “Glass Tank” Sand Specimens

4.1 Overview

The bench top experiments described in Chapter 3 demonstrated the ability of electric conductivity probes to evaluate the rate of reaction of sodium percarbonate or rate of gas generation leading to reduction in degree of saturation, as well as to provide estimates of the degree of saturation at the location of a probe. To explore the additional capabilities of conductivity probes in the implementation of IPS, probes were included in laboratory sand specimens subjected to two-dimensional IPS process. The two-dimensional sand specimens were prepared in especially constructed relatively large glass tank.

The purpose for conducting the “glass tank” experiments was two folds: 1) to implement, in the laboratory, IPS in a manner similar to a field application of IPS, and monitor the process, and record and use the data to validate SUTRA-Bubble, a software developed by another doctoral student, Seda Gokyer, which models and simulates an IPS process, 2) to explore the benefits of using electric conductivity probes in IPS implementation.

This chapter describes the use of electrical conductivity in monitoring and evaluating IPS in the laboratory experiments. A glass tank test entailed, placement of conductivity probes and pore water pressure transducers at various locations within the glass tank. By raining, dry Ottawa sand, a fully saturated sand specimen was then prepared. From the center of the specimen, sodium percarbonate solution with a desired concentration was injected, and measurements of flow, injection pressure, pore pressures, and electric conductivities were made during and after the completion of the injection of the chemical solution. Two glass tank tests were conducted on almost identical sand specimens, but subjected to different concentrations of the chemical solution. In the first test, (Test 1) the
concentration was 1%, and in the second test, (Test 2) it was 0.5%. The second test was performed to ensure the validity of the test results from Test 1, and to evaluate the effect of concentration on the IPS process and results.

4.2 Test set up and specimen preparation procedure

The experimental set up was designed to simulate injection of sodium percarbonate solution with controlled concentration and pressure. A glass tank was constructed having dimensions: 60cm x 91cm x 13.5cm. The sidewalls were made of glass to allow clear viewing and photo capturing of the response of the sand specimen to IPS.

Figure 4-1 is a photo of the glass tank taken prior to the placement of the sand. The photo also shows the injection tube placed in the center of the tank, and twelve conductivity probes hanging by their cables, which eventually would be monitoring the IPS process in the sand specimen.

Figure 4-1 Empty glass tank with injection tube and electric conductivity probes

A 2.3 cm diameter open-ended plastic tube, placed 30 cm from the bottom of the tanks, was used for injection of the chemical solution. To maintain symmetry of the injection, the tip of the injection tube was placed level. A relief valve was attached to the top of the injection tube to release any gas generated inside the tube during injection. As the injection
duration was short in both tests (13 minutes), the amount of gas accumulated in the injection tube was very small and the relief valve was rarely used. The tip of the injection tube was covered with geotextile to prevent sand penetrating the tube. The electric conductivity probes were essential components of the experiments and allowed monitoring of the IPS process from arrival of the chemical solution to gas generation, and ultimately estimating the degree of saturation at the probe locations. Figure 4-2 identifies the probe numbers and their locations within the glass tank.

![Electric conductivity probes in the glass tank specimen](image)

Figure 4-2 Electric conductivity probes in the glass tank specimen

A fully saturated sand was prepared by raining approximately 100 kg of dry Ottawa sand (C778) into clean water placed in the glass tank. This method resulted in a very loose fully saturated sand specimen. The void ratios of the two specimens were: 0.69 in Test 1, and 0.72 in Test 2. Figure 4-3 shows the process of specimen preparation and the final size of the specimen in Test 1.
Figure 4-3 Glass tank specimen preparation, Test 1

A Marriott bottle fixed to one of the building columns was used to inject the chemical solution under a desired constant pressure. Figure 4-4 shows the Marriott bottle and its connection to the specimen with a plastic tube.

The Marriott bottle was manufactured out of Plexiglas with 2.3 cm diameter outlet (same as tip of the injection tube). The capacity of bottle is about 16 liters. The bottle is a completely sealed system with a standpipe inside. One end of the standpipe sits inside the injection solution and the other end heads out of the bottle and is open to the atmosphere. Total head everywhere in the tank is equal to total head at the tip of standpipe, and can be calculated by adding atmospheric pressure head and elevation head of that point. The head difference applied by the Marriott bottle can be calculated by subtracting the elevation of
the bottom end of the standpipe from the elevation of free water on top of a specimen. Total head applied in both experiments was 27.15 cm. The loss of head from Marriott bottle to injection tip was very small and negligible (about 1 cm). Details on the Marriott bottle and its operation during IPS can be found in the dissertation by Seda Gokyer (2015). A scale was placed under the Mariette bottle to measure the inflow. The difference between inflow and outflow from a specimen represents the amount of gas generated in the specimen and was used to calculate the average degree of saturation in the specimen.

Figure 4-5 shows a schematic drawing of the glass tank experiment including injection components. The 27.15 cm head difference applied for injection is shown in the figure.

![Schematic drawing of the glass tank and the IPS injection components](image)

Figure 4-5 A schematic drawing of the glass tank and the IPS injection components

The injection duration was 13 minutes in both Test 1 and Test 2.

4.3 Test Results

The experimental tests results recorded included the injection pressures, rates of inflow and outflow of the solution, pore water pressures, and electric conductivity. In this
dissertation, analyses of the electric conductivity data from the glass tank tests are presented to demonstrate the capability of conductivity probes to:

1- Monitor the transport of the chemical solution, and observe the zone of IPS treatment of the sand specimens
2- Provide reliable estimates of degree of saturation

In the following sections, the experimental results from Test 1 are presented first followed by the results from Test 2.

4.3.1 Test 1 (1% concentration)

In Test 1, the void ratio of the sand specimen was 0.69. The chemical solution was injected for 13 minutes. During and after injection, the electric conductivities of each probe were recorded.

4.3.1.1 Transport of chemical solution during injection

Figure 4-6 shows a photo of the glass tank specimen of Test 1, on top of which plots of the electric conductivities recorded by each probe are overlain. Figure 4-6 helps to observe the transport of the chemical solution during the injection under the applied constant pressure (process referred to as Advection flow). Just before the start of injection, all probes recorded the electric conductivity of the clean water and sand (in the range of 0 mS/cm to 0.1 mS/cm). When the solution arrived at a probe, the electric conductivity increased up to a peak value determined by the concentration of the solution that was being injected. Figure 4-6 shows that electric conductivity at different locations increased at different times. For instance, electric conductivity of probes which were very close to the tip of the injection tube (CP1 and CP2) increased right after injection started (within a minute), but for CPs which were farther from the injection tube (CP9 and CP4), it took about 4 minutes for electric conductivity to start increasing. Conductivity probes CP10, CP11, and CP12 did not show any change in electric conductivity value during injection, which indicates that the solution did not reach to the locations of these probes during the 13 minutes of injection.
In Figure 4-6, probes CP1 through CP9 showed increase in electric conductivity in relatively short time (during injection). Electric conductivity value at CP10, CP11, and CP 12 did not increase during the experiment. It can be concluded from the CP data that the radius of influence of injection of solution is somewhere between CP9 and CP11, near the top of the sand specimen, and between CP8 and CP10 near the bottom. The peak electric conductivity values recorded by CP1 through CP9 are between 2.8mS/cm to 3.7 mS/cm, which compare well with the values recorded in the bench top tests when the concentration of the solution was 1% (between 2.2mS/cm-3.3mS/cm). It is concluded that the maximum concentration of solution reached at probes CP1 through CP9.

The black line on Figure 4-6 shows the zone of influence observed visually (approximate radius of 25 cm), which is consistent with the zone of influence indicated by the conductivity probes discussed in the previous paragraph. The numerical simulation performed using SUTRA-Bubble also indicated a radius of influence of 24 to 27 cm, for the chemical solution, as shown in Figure 4-7, which matches very well with the CP data.
and visual observation. Figure 4-9 shows contours of concentration of the solution predicted by SUTRA-Bubble.

![Concentration Output of SUTRA-Bubble](image)

**Figure 4-7 Zone of influence predicted by SUTRA-Bubble, Test 1**

It is observed from Figure 4-6 that at CPs located close to tip of the injection tube (for example, CP1 and CP2), the rise in electric conductivity value due to arrival of solution was abrupt. For CPs which were located further from the injection tube (for example, CP8 and CP4) this rise was more gradual and S-shaped. To explain the difference in the shape of electric conductivity plots at different CP locations, the theory of transport of chemical during injection is used. The chemical transport in sands is governed by advection-dispersion theory. Another benefit of studying the transport of chemical is estimating dispersivity and molecular diffusion coefficients in the sand specimen tested. These parameters were needed in the numerical modeling of IPS by SUTRA-Bubble. The following paragraphs will describe the advection-dispersion flow theory, and the estimation of dispersivity and molecular diffusion coefficients.
Figure 4-8 shows typical effect of advection and dispersion flows on the change in concentration at a point within a specimen of sand.

![Graph showing typical effect of advection and dispersion flows](image)

Figure 4-8 Rise in concentration as a result of advection-dispersion flow

The solid red line shows the change in concentration when the chemical transport is governed primarily by advection flow with insignificant dispersion effect. When dispersion effect is very small, concentration changes abruptly from zero to a maximum value of $C_0$. The black dashed line shows the change in concentration when the transport is governed by advection with significant dispersion effect. In this case, the change in concentration at a point is gradual and follows a typical S-shape, as suggested by Palmer and Johnson, (1989a).

Referring to the conductivity plots shown in Figure 4-6, it is observed that at probes which were located close to injection tube (CP1, CP2, CP3, and CP5) the effect of dispersion was insignificant and the rise in electric conductivity was primarily due to advection flow. Advection flow is governed by seepage velocity, which is higher near the injection tube than farther away from it. At probe locations farther away from the injection tube (CP4, CP6, CP7, CP8, and CP9) dispersion compared with advection played some role, though not very significant. Overall, the effect of dispersion in flow was very small during injection of solution weather close or far from the injection tube.

To estimate the advection-dispersion coefficients from the electric conductivity data, Equation 4-1, which describes transport of chemical solution in sand is presented.
\[ \frac{\partial c_i}{\partial t} = D_x \frac{\partial^2 c_i}{\partial x^2} - V_s \frac{\partial c_i}{\partial x} \quad (4-1) \]

In Equation 4-1, \( c_i \) is concentration of species \( i \) (ML\(^{-3}\)), \( V_s \) is seepage velocity (LT\(^{-1}\)), which is governed by Darcy’s law and \( D_x \) is hydrodynamic Dispersion coefficient (L\(^2\)T\(^{-1}\)). Hydrodynamic dispersion coefficient is summation of molecular diffusion and mechanical dispersion presented in Equation 4-2.

\[ D_x = \text{Molecular diffusion} + \text{Mechanical Dispersion} = D^*_0 + \alpha V_s \quad (4-2) \]

In Equation 4-2, \( \alpha \) is dispersivity (L) and \( D^*_0 \) is molecular diffusion coefficient in sand (L\(^2\)T\(^{-1}\)). Typical value for dispersivity in homogeneous sand is \( 10^{-3} \) to \( 10^{-1} \) m (Gillham and Cherry, 1982) and molecular diffusion coefficient for sodium (Na\(^+\)) and carbonate (CO\(_3^{2-}\)) are \( 13.3 \times 10^{-10} \) and \( 9.55 \times 10^{-10} \) m\(^2\)/s (Mohamed and Antia, 1998). Equation 4-1 was solved numerically using SUTRA-Bubble, and the concentration of chemical solution each probe location was computed, as a function of time. To solve equation 4-1 by SUTRA-Bubble a pair of dispersivity and molecular diffusion coefficient close to typical values were used (\( \alpha = 10^{-3} \) m and \( D^*_0 = 10^{-9} \) m\(^2\)/s). The details of the numerical modeling by SUTRA-Bubble are presented in the dissertation by Seda Gokyer. The concentration of chemical solution predicted by SUTRA-Bubble and the electric conductivity, which represents transport of the chemical solution, can be compared to verify the suitability of the values of dispersivity and molecular diffusion used in solving Equation 4-1 by SUTRA-Bubble. Because the units of concentration computed by SUTRA-Bubble is different from the one measured by conductivity probes (mS/cm), both curves were normalized to their peak values. Figure 4-9 shows comparisons of the normalized measured electric conductivity plots (labelled Experiment) with plots of normalized concentration curves predicted by SUTRA-Bubble (labelled Model).
Figure 4-9 Comparisons of normalized conductivity based on experimental data, or normalized concentration based on Model, Test 1.

The reasonably good agreement observed between the Experiment and Model normalized curves shown in Figure 4-9 confirm that dispersivity and molecular diffusion values used in SUTRA-Bubble ($\alpha = 10^{-3}$ m and $D^*_0 = 10^{-9}$ m$^2$/s) were appropriate for the sand specimen tested.

### 4.3.1.2 Degree of saturation

The degree of saturation at each conductivity probe location was calculated using the electric conductivity values measured and the procedure described in Chapter 3.

Figures 4-10 through 4-14 present electric conductivity data as well as degree of saturation at probe locations CP1 through CP9. As was explained in the previous section, sodium percarbonate solution did not reach probes CP10, CP11, and CP 12, and hence degree of saturation was assumed to be 100% at these probe locations. Included in degree
of saturation plots of Figures 4-10 through 4-14, are degree of saturation at each probe location computed by SUTRA-Bubble. These plots are referred to as Model results.

Figure 4-10 Electric conductivity and degree of saturation at probe locations CP1 and CP2, for Test 1
Figure 4-11 Electric conductivity and degree of saturation at probe locations CP3 and CP5, for Test 1
Figure 4-12 Electric conductivity and degree of saturation at probe locations CP4 and CP8, fir Test 1
Figure 4-13 Electric conductivity and degree of saturation at probe locations CP6 and CP7, for Test 1
At some probe locations, the electric conductivity data near the end of the recording time, when gas generation was essentially complete, show slightly erratic trend. This trend should be either flat, no longer gas generation, or increasing indicating gas bubble escape. These isolated erratic data are attributed to the low resolution of the probes and their meters (0.1 mS/cm). These few erratic data points (identified with black triangles on the plots) were excluded in the comparisons made between the recorded and Model based degree of saturation. The excluded data are shown in each plot using black triangles.

For each probe location, the final degrees of saturation was computed, using the electric conductivity data when there were little changes in the values as a function of time. Figure 4-15 shows the values at each probe location. The range of degree of saturation
computed within the zone of influence is between 59% and 73%, with an average value of 65%. This compares well with degree of saturation obtained from the bench top tests for 1% concentration (60%).

An additional set of calculations was made to estimate the average degree of saturation of the partially saturated zone of the specimen using equations of phase relations. This approach was similar to that described in Chapter 3 and referred to as volume based calculations.

The difference between outflow and inflow volumes represented the volume of gas bubbles trapped in the sand pores. Volume of void can be calculated knowing the total mass of soil used in the specimen and the total volume of the specimen. Details of the calculations of volume of void and degree of saturation based on phase relation equations are given in Chapter 2. The specific values of these parameters for the sand specimen of Test 1 are:

\[ \text{outflow} - \text{inflow} = V_a = 4292 \text{ cm}^3 \]
\[ V_v = 27008 \text{ cm}^3 \]
Volume of the partial saturation zone as observed visually was between 55% to 60% of the total specimen.

$$V_v$$ of partial saturation zone = \((0.55 \text{ to } 0.6) \times 27008 = (14855 \text{ to } 16205) \text{cm}^3\)

Degree of saturation can be calculated by the ratio of volume of water in sand pores \((V_v - V_a)\) to the volume of void.

Assuming 55% zone of partial saturation

$$S_{avg} = \frac{14855 - 4292}{14855} \times 100 = 71\%$$

Assuming 60% zone of partial saturation

$$S_{avg} = \frac{16205 - 4292}{16205} \times 100 = 74\%$$

The average degree of saturation calculated based on equations of phase relation (71% to 74%) indicates slightly higher degree of saturation compared to the one calculated based on electric conductivity data (65%) or from the bench top test (60%). This difference is most probably due to measurement errors in the volume of outflow. Nevertheless, the rough calculations using equations of phase relations confirm that the degrees of saturation estimated based on electric conductivity are reasonable.

### 4.3.2 Test 2 (0.5% concentration)

To confirm the validity of the glass tank experimental results from Test 1, and to evaluate the effect of concentration on various parameters and electric conductivity trends observed a second test (Test 2) was performed. In Test 2, the concentration of injected solution was 0.5%., and the void ratio of the specimen was about 0.72, very slightly larger than that of Test 1 (0.69). This section describes the results of Test 2.

#### 4.3.2.1 Transport of chemical solution during injection

Figure 4-16 shows a photo of the glass tank specimen of Test 2, on top of which plots of electric conductivity at each probe are overlain. Figure 4-16 helps to study the transport of chemical solution in Test 2. When the solution arrived at a probe, the electric conductivity increased up to a peak value determined by concentration of the solution. Figure 4-16 shows that probes which were close to the injection tube (CP 1 and CP2) showed quick rise in electric conductivity right after injection (within 1 minutes), while at CP9 and CP4, which were farther from the injection tube, it took about 4 minutes for
electric conductivity to start increasing. Similar behavior was observed in Test 1 (Figure 4-6).

![Diagram showing electric conductivity results](image)

Figure 4-16 Electric conductivity results during 13 minutes of injection Test 2

EC on vertical axes of each plot in Figure 4-6 represents electric conductivity.

In Figure 4-16, probes CP1 through CP9 (Except CP8) showed increase in electric conductivity in relatively short time (during injection). CP8 was also able to detect the arrival of chemical but about 30 minutes after the start of injection. This late arrival is due to diffusion, as will be explained in later in this section. Electric conductivity values at CP10, CP11, and CP12 did not increase during the experiment. Maximum electric conductivity values at probes CP1 through CP9 locations were 1.5 mS/cm to 2.4 mS/cm, while this value was 1.5mS/cm in the bench top experiments. It is concluded that maximum concentration of solution (0.5%) reached CP1 through CP9 locations. Peak values of electric conductivity in Test 2 (1.5mS/cm to 2.4mS/cm) were smaller than in Test 1 (2.8mS/cm to 3.7mS/cm), which is because of lower concentration of solution injected in Test 2.
Based on conductivity probe readings, it is concluded that somewhere between CP9 and CP11, at shallow depth of the specimen, and CP8 near the bottom of the specimen define the zone of influence of injection (approximate radius of 20 cm). As advection flow primarily governs the chemical solution transport, and Tests 1 and 2 were identical in advection flow parameters (head difference, specimen dimensions) except small difference in permeability, it was expected to observe same size of zone of influence in Tests 1 and Test 2. However, zone of influence in Test 2 was smaller than in Test 1. It is noted that while conducting Test 2 after saturating the injection tube with chemical solution, there was a 10 minutes unintended wait before starting the main injection. It is speculated that within the 10 minutes of delay in injection the solution generated enough gas bubbles that clogged the geotextile present at the tip of the injection tube, thus reducing its efficiency (or cross sectional area). This can be an explanation for the smaller zone of chemical solution transported in Test 2. Figure 4-16 shows a black line (approximate radius of 20 cm) that was established visually as the zone of transport of the solution and partial degree of saturation, which is very similar to that established using the electric conductivity measurements (approximate radius of 20 cm).

Figure 4-17 shows the results of the glass tank experiment Test 2 simulated using SUTRA-Bubble. The contours of concentration show that the chemical solution, during the 13 minutes of injection, reached out to about 23 cm from the injection tube. This zone of influence matches well with the 20 cm radius determined using electric conductivity data and by visual observations of partial saturation zone.

Figure 4-17 represents zone of influence of injection predicted by SUTRA-Bubble.
It can be observed from Figure 4-16 that similar to Test 1, the rise in electric conductivity measured by probes which were located close to injection tip (CP 1, CP 2, CP3, and CP5) were more abrupt than the ones which were located relatively far from the injection tip (CP4, CP6, CP7, CP 8, and CP 9). Overall, it can be concluded that the effect of dispersivity in advection-dispersion flow was very small and negligible.

Similar to Test 1, Equation 4-1 was solved numerically by SUTRA-Bubble. Same dispersivity and molecular diffusion coefficient were used in SUTRA-Bubble ($\alpha = 10^{-3}$ m and $D^* = 10^{-9}$ m$^2$/s). Comparisons of normalized electric conductivity measured at each probe location (Experiment) with normalized concentration of chemical solution predicted by SUTRA-Bubble (Model) are presented in Figure 4-18.
The agreements between the Experimental and Model results are good except for CP8. Figure 4-19 shows the data for CP8 for longer duration, up to 150 minutes.
Figure 4-19 shows that the chemical solution arrived at the location of CP8 after the completion of injection by diffusion. The predicted arrival of solution by SUTRA-Bubble was earlier than the measured data. It is noted that the travel distance for concentration of solution by diffusion is very small (in the order of 3-4 cm). Therefore, the prediction of arrival time of the chemical solution was very sensitive to the selection of the precise probe location in SUTRA-Bubble. Predicted arrivals at a slightly different location near CP8, showed significantly different arrival time that is shown in Figure 4-19. Therefore, the poor match of the normalized curves at CP8, most likely is due to inability to precisely locate CP8 on the SUTRA-Bubble mash.

Generally good match observed between the normalized plots shown in Figure 4-18 confirm that the dispersivity and molecular diffusion coefficients used in SUTRA-Bubble ($\alpha = 10^{-3} \text{ m}$ and $D^* = 10^{-9} \text{ m}^2/\text{s}$) were good choices.
4.3.2.2 Degree of saturation

Similar to Test 1, the degree of saturation at each conductivity probe location was calculated using the electric conductivity values measured and the procedure described in Chapter 3.

This section describes degree of saturation calculated based on electric conductivity values for Tests 2. Figures 4-20 through 4-24 present electric conductivity data as well as degree of saturation for probe locations CP1 through CP9. As it was explained in the previous section, the chemical solution did not reach probes CP10, CP11, and CP12, and therefore degree of saturation was assumed 100% at these probe locations. In Figures 4-20 through 4-24, degree of saturation computed by SUTRA-Bubble at each probe location are included. These plots are referred to as Model results.
Figure 4-20 Electric conductivity and degree of saturation at probe locations CP1 and CP2, for Test 2
Figure 4-21 Electric conductivity and degree of saturation at probe locations CP3 and CP4, for Test 2
Figure 4-22 Electric conductivity and degree of saturation at probe locations CP4 and CP8, for Test 2
Figure 4-23 Electric conductivity and degree of saturation at probe locations CP6 and CP7, for Test 2
Figure 4-24 Electric conductivity and degree of saturation at probe location CP9, for Test 2

In Figures 4-20 through 4-24 the electric conductivity data points identified with black triangles are the data excluded in the comparisons made of degree of saturation between measured data and predicted by SUTRA-Bubble (Model). The reasons for excluding these isolated few data was presented in Section 4.3.1.2.

The final degrees of saturation at the probe locations were computed, using the electric conductivity data. Figure 4-25 shows degree of saturation at the location of each probe within the glass tank specimen in Test 2. The range of degree of saturation computed within the zone of influence is between 65% and 77%, except at CP6, which is about 54%. This range compared with that from for Test 1 (59% to 73%) is higher because of lower concentration of the chemical solution used in Test 2 (0.5% versus 1%). The average...
degree of saturated computed based on electric conductivity within the zone of influence in Test 2 was 68%. This compares well with the average degree of saturation obtained from bench top test for 0.5% concentration of solution (73%).

Figure 4-25 Final degree of saturation calculated at each probe location, Test 2

Similar to test one and additional set of calculation were made to estimate average degree of saturation of the partially saturated zone of the specimen. The method was similar to that described in Chapter 3 and referred to as volume-based calculation.

The difference between outflow and inflow volumes represents the volume of gas bubbles trapped in sand pores. The specific values of these parameters for the sand specimen of Test 2 are:

\[
\text{outflow} - \text{inflow} = V_a = 1483 \text{cm}^3 \\
V_v = 28209 \text{ cm}^3
\]

Volume of the partial saturation zone as observed visually was 40% to 45% of the total specimen.

\[
V_v \text{ of partial saturation zone} = (0.4 \text{ to } 0.45 ) \times 28209 = (11283 \text{ to } 12694) \text{ cm}^3
\]
Assuming 40% zone of partial saturation = $S_{avg} = \frac{11283 - 1483}{11283} \times 100 = 86\%$

Assuming 45% zone of partial saturation = $S_{avg} = \frac{12694 - 1483}{12694} \times 100 = 88\%$

The average degree of saturation calculated based on equation of phase relation (86% to 88%) indicates higher degree of saturation compared to the one calculated based on electric conductivity data (68%) as well as from bench top tests (73%). This difference is most probably due to measurement errors in volume calculation method especially measurement of outflow which is smaller in Test 2 and harder to capture the water and measure its volume accurately.

4.4 Summary and Conclusions

Electric conductivity probes were implemented in relatively large sand specimens prepared in a glass tank to monitor laboratory application of IPS and to determine the benefits of measuring electric conductivity in defining the zone of partial saturation, and providing estimates of degree of saturation. Two tests were conducted with the only difference in the concentration of the chemical solution used in inducing partial saturation (1% and 0.5%).

Based on the experimental test results, the following conclusions are made:

1- Conductivity probes placed at varying distances from an injection tube can help establish the zone of partial saturation.

2- Electric conductivity reading and the procedure for calculating degree of saturation, can yield reasonable estimates of degree of saturation comparable with what is predicted with numerical simulation of two-dimensional application of IPS.

3- Electric conductivity readings obtained from two-dimensional application of IPS in a large sand specimen and from bench top tests are similar for a given concentration of the chemical solution.

4- Advection flow dominates chemical transport in sands and the effect of diffusion and dispersivity are very small. Dispersivity and molecular diffusion coefficients are two main parameters in advection-dispersion equation which are essential in numerical modeling by SUTRA-Bubble. These parameters can be back
calculated by fitting the theoretical data from solving advection-dispersion equation to measured electric conductivity data. For the sand specimens tested, dispersivity and molecular diffusion coefficients were $\alpha = 10^{-3}$ m and $D^*_{0} = 10^{9}$ m$^2$/s, respectively.
Chapter 5

Use of Electric Conductivity Probes for Monitoring IPS in Large-Scale Laminar Box Sand Specimens

5.1 Overview

Chapter 4 presented experimental test results from application of IPS in sand specimens prepared in a large glass tank. Electric conductivity probes were used to monitor the two-dimensional flow and reactivity of sodium percarbonate solution injected to reduce the degree of partial saturation of initially fully saturated sand specimens. The benefits of using the probes and their crucial role in interpreting the IPS test results from the glass tank were demonstrated. The glass tank experiments did not include shaking of the partially saturated sands to evaluate the effect of IPS on liquefaction response of the sand specimens. The tests were conducted to obtain experimental data on flow and reactivity of the chemical solution to validate the numerical simulation software SUTRA-Bubble, and to investigate the benefits of using electric conductivity to monitor this process.

Upon completion of the bench-top and glass tank IPS tests, another phase of the research project was launched at the NEES@Buffalo experimental facility. This laboratory has a large laminar box (5m x 2.75m x 6m) in which a sand specimen can be prepared and shaken at its base with large hydraulic actuators. The overarching purpose of two tests that were performed using the laminar box was to evaluate the implementation of the IPS process, the monitoring techniques using electric conductivity probes, and the benefits of IPS in mitigating liquefaction effects, under representative field conditions.

This chapter presents details of two laminar box tests and the results focused on the role of electric conductivity probes in monitoring IPS and providing estimates of degree
of saturation to help interpret the shaking test results. The primary difference in the two laminar box tests was in the process of reducing the degree of saturation of the initially fully saturated specimens. The preparations of the two fully saturated sand specimens were identical, resulting very similar initial relative densities.

In the first test (Test 1), IPS was implemented by using injection tubes that were hanging in the laminar box prior to filling it with the fully saturated sand. This technique resulted in partially saturating the middle zone of the specimen. Additional injections were made from the top of the specimen to reduce the degree of saturation of the top 2m region of the specimen. In this test, about 1m of the bottom of the specimen remained fully saturated.

In the second test (Test 2), the fully saturated sand specimen was prepared without prior insertion of injection tubes. After a fully saturated sand specimen was prepared in the laminar box, IPS was implemented by using injection tubes jetted down to the bottom of the specimen and then slowly retrieved while injecting the chemical solution.

After partially saturating both test specimens, they were shaken and the excess pore water pressures were recorded, and the benefits of IPS were evaluated. The shaking table test results are presented in an upcoming dissertation by Fritz Nababan. Throughout both tests, starting from injection of the chemical solution, during wait time for generation of gas bubbles, and during and after shaking, the data from conductivity probes placed in the sand specimens were recorded. This chapter presents the conductivity data and its analysis demonstrating the benefits of using conductivity probes in this research.

5.2 Introduction to the Laminar Box

The laminar box at NEES@Buffalo is a large steel box with dimensions of 5m x 2.75m x 6m. The box is made of 39 stacked 6-inch height laminates (I-beam-cross section) and rests on top of a shaking table. The laminar box can be shaken under harmonic and real free-field seismic motions. The shaking direction is East-West. Figure 5-1 presents the dimensions of the laminar box in plan and elevation views as well as the direction of shaking.
Figure 5-1 Plan and elevation views of the laminar box
Figure 5-2 shows the laminar box on top of the shaking table and the laminates instrumented with accelerometers and potentiometers (LVDT).

5.3 Preparation of fully saturated sand specimens

Two tests were conducted using the laminar box to evaluate the effect of IPS in reducing liquefaction potential under harmonic excitations. In each of the two tests, first a fully saturated sand specimen was created within the box, then a process of IPS was implemented to reduce the degree of saturation of the specimen, and finally the specimen was shaken and data were recorded to evaluate the liquefaction response of the specimen. In both tests, the preparation of a fully saturated sand specimen was identical, resulting in specimens with similar size and density.
In Test 1, prior to the filling of the laminar box with sand, six (6) PVC tubes that were later used as injection tubes, were hanged from a steel truss located above the laminar box. Also, within five wire meshes ten (10) conductivity probes and twelve (12) pore water pressure transducers were attached and the meshes were also hanged from the steel truss. The laminar box was then hydraulically filled with mixture of water and sand pumped from sources located outside of the laboratory building. Bucket samples were taken to measure the relative density of the sand specimen created. Pore pressure transducers were read during and after the placement of the fill, confirming that the sand specimen is indeed fully saturated.

In Test 2, there were no injection tubes placed in the box prior to filling it. Thirteen (13) conductivity probes and thirteen (13) pore water pressure transducers were attached to five meshes that were hanged in the empty laminar box. Additional eight (8) conductivity probes (for a total of 21 probes) were hanged at various locations within the box to monitor the degree of saturation across the entire sand specimen. Placement of the sand and water to create a fully saturated sand specimen was as in Test 1.

More details of the instrumentation the IPS process are presented in subsequent sections.

5.4 Preparation and injection of chemical solution

An automated preparation of sodium percrabonate solution having a desired concentration and its injection into in laboratory or field sand deposits under a constant pressure was designed and manufactured by Fritz Nababan. This system was used to implement IPS in the sand specimens of the laminar box. Figure 5-3 shows a photo of the IPS deliver system, which includes a source of clean water, powder supply and mixing system, and a constant pressure injection pump.
The automated powder supply and mixing operation can be adjusted to achieve a desired concentration of the chemical solution. Additional checks on the actual concentration of the prepared solution were made by using a Brix probe (pen refractometer supplied by ATAGO USA, Inc., Figure 5-4) and a Milwaukee electric conductivity probe.

Figure 5-4 Brix probe to check concentration of chemical solution
The BrixBrix probe measured directly the concentration of the chemical. The electric conductivity probe was used to measure indirectly the concentration of the chemical solution by relating electric conductivity to concentration of sodium percarbonate solution in clean water. This relationship was established in bench-top tests using sodium percarbonate solutions having different concentrations. Figure 5-5 shows the test results, which indicate that the relationship between electric conductivity and concentration of sodium percarbonate solution is linear. This relationship was used during the preparation and delivery of the chemical solution by checking the electric conductivity. For example, for a desired concentration of 1%, target electric conductivity was about 10 mS/cm.

Figure 5-5 Electric conductivity versus concentration of sodium percarbonate solution

The process of preparation of the chemical solution and its injection typically takes about 15 to 20 minutes. The chemical reaction starts as soon sodium percarbonate is introduced into the clean water. It was important to know if the rate of decomposition of sodium percarbonate was significant or not within this window of time 15 to 20 minutes of IPS injection, and if this rate depended on the concentration of the chemical solution.

Figure 5-6 shows the laboratory test set-up that was used to measure the rate of reaction of sodium percarbonate in water.
Figure 5-6 Experiment set up for studying the reaction of sodium per carbonate in water

A chemical solution of a known concentration was drawn into a pipet and then the top of the pipet was closed using a shut-off valve. While the reaction generated oxygen bubbles that accumulated at the top of the vertically held pipet, solution dripped out of the tip of the pipet, forced by the volume of gas accumulated at the top. The volume of solution expelled was recorded at various times and normalized with the volume of the remaining solution at that time. This ratio plotted as a function of time indicated the rate of the reaction of sodium percarbonate in clean water. Figure 5-7 shows the test results, for concentrations of 0.5%, 1%, and 2%.

Figure 5-7 Rate of reaction of sodium percarbonate solution in clean water
The experimental test results indicate that the rate of decomposition of sodium percarbonate depends on the concentration of the solution. The higher the concentration is, the faster is the chemical reaction. In any case, regardless of the concentration (ranging between 0.5% to 2%), very little of the chemical reaction takes place within the 15-20 minute window of preparation and injection of the solution, in typical IPS applications.

5.5 Typical electric conductivity test result from the laminar box

The injection of sodium percarbonate solution into the laminar box specimens initiated a number of processes including transport of the solution, reactivity leading to generation of gas bubbles, potential gas bubble escape, and dilution and diffusion of ions from high concentration to lower concentration regions. The electric conductivity probes were able to capture these processes. In this section, a typical record of electric conductivity is used to explain how the data were interpreted and used in this research.

Figure 5-8 shows the electric conductivity record of CP1 obtained in Test 2.

![Sample Electric Conductivity Plot](Image)

Figure 5-8 Typical electric conductivity plot with explanations of detected events.
The following explanations are provided referring to Figure 5-8:

1. The electric conductivity of the fully saturated Ottawa sand is about 0.2 mS/cm. The first recording of a value larger than this is an indication of the arrival of the chemical solution at the probe location.

2. As more of the solution arrives and increases the chemical concentration of the water at the probe location, the electric conductivity increases to a maximum value (point A) indicating that the concentration of the water at the probe location is the same as the injected solution.

3. As the reaction takes place, oxygen gas is generated and the electric conductivity of the sand at the probe location decreases (as explained in Chapter 2), to a minimum value (point B), indicating the completion of the reaction and gas bubble generation.

4. Sometimes, gas bubbles escape possibly due high gas pressure and or increased flow velocities induced by additional injections made near the probe. Loss of gas bubbles results in increase in electric conductivity up to point C on the plot.

5. In addition, an injection from a point near the probe location can push clean water present between the injection point and the probe, thus diluting the solution at the probe location. This will decrease the electric conductivity.

6. An injection from a point near the probe location might push water containing sodium and carbonate ions (no hydrogen peroxide and hence no bubble generation) towards the probe, thus increasing the electric conductivity.

7. The degree of saturation at the end of bubble generation can be calculated by

\[ S_B = \sqrt{\frac{B}{A}} \]  

(as explained in Chapter 2), where B and A are the electric conductivity values at points B and A.

8. The degree of saturation including gas bubble generation (point C) can be calculated by

\[ S_C = \sqrt{\frac{B}{A}} \times \sqrt{\frac{C}{B}} \]  

based on Archie’s law (refer to Chapter 2).
5.6 Electric conductivity results from laminar box Test 1

5.6.1 Specimen preparation: Test 1

In Test 1, prior to the placement of the fully saturated sand in the laminar box, six (6) 2.54 cm in diameter PVC pipes and five steel wire meshes were hanged from a fixed steel truss located above the top of the laminar box. Tied to the meshes were ten (10) Milwaukee electric conductivity probes with extended cables and twelve (12) pore water pressure transducers placed at desired depths within the box.

Figure 5-9 a) steel wire mesh with conductivity probes attached, b) Milwaukee conductivity probes with extended cables, and c) ten probe meters used in Test 1
Figure 5-9 shows a steel wire mesh prior to hanging in the laminar box, a typical conductivity probe, and the ten probe meters used to record the data. The locations of the ten CPs were selected to be near the pore pressure transducers fixed in the five steel wire meshes.

Figure 5-10 shows the PVC injection tubes and steel meshes hanging from the steel truss, at desired positions within the laminar box.

A fully saturated sand specimen was prepared by hydraulically filling the laminar box with Ottawa sand until the height of the specimen was 4.88m (16 feet). Figure 5-11 shows the size of the sand specimen and the locations of the 10 electric conductivity probes (CPs).
Figure 5-11 Plan and elevation views of the laminar box showing locations of electric conductivity probes, in Test 1
As shown in Figure 5-11, these meshes were placed in the southern half of the laminar box, allowing the placement of the hydraulic fill from the northern half of the box. This limited electric conductivity data to this instrumented section of the laminar box, thus providing knowledge about the partial saturation status only this region. The quality of IPS treatment in the northern section of the box was not ascertained. A major handicap faced in Test 1.

### 5.6.2 IPS treatment: Test 1

In this test, the six PVC pipes that were hanged prior to filling of the laminar box were used to inject the chemical solution. Figure 5-12 shows a photograph of the three injection tubes IT2, IT4, and IT5 located within the western region of the specimen.

![Injection Tubes](image)

**Figure 5-12 Photograph of injection tube IT2, IT4, and IT5**

Figure 5-13 shows the locations of all six injection tubes (IT1 through IT6). The original intent was that the tips of the tubes located at about 3m from the surface of the sand specimen, would be able to induce partial saturation within the entire specimen. It was later determined, using the conductivity probe data, that only about 2m depth around the injection tubes partial saturation was achieved. This was attributed to the constrictions created by the geotextiles that were placed at the tips of the injections tubes.
to prevent intrusion of sand into the tubes. The upper 2 meters and about 1 meter of the bottom of the specimen were not treated by using the six injection tubes.

Figure 5-13 Locations of six injection tubes and the treated zone by the tubes, in Test 1
After the chemical injection was completed using the six PVC tubes, it was decided to proceed treating the top 2 meters of the specimen using a 0.5” (1.27 cm) diameter and 8’ (2.5 m) long injection tube.

Figure 5-14 Locations of injection points used to treat the top 2m of the specimen, in Test 1
The tip of the injection tube was closed with a cone. About 12 inches of the bottom section of the tube was perforated to allow horizontal injection. The tube was jetted into the sand specimen from its surface down to about 2 meters, and then slowly retrieved while maintaining the injection of the solution. Figure 5-14 shows the locations of the injection of the chemical solution to treat the top 2 meters of the specimen in Test 1.

Figure 5-15 shows photographs of the jetting and injection processes performed from the top of specimen for IPS treatment of the top 2 meters, in Test 1.

Further details of the injection process and data can be found in an upcoming dissertation by Fritz Nababan.

### 5.6.3 Electric conductivity results: Test 1

During Test 1, electric conductivity at each probe location was recorded from the start of injection (both from the six PVC tubes and the surface injection tube) till long after gas bubble generation was completed. Electric conductivity readings were also taken before and after the Test 1 sand specimen was subjected twice to large excitations by the shaking table.
Analysis of the electric conductivity data was performed to investigate the effect of the various stages of injection of the chemical solution on the partial saturation of the sand. Specifically, conclusions were drawn regarding the transport of the solution and hence the zone of influence of IPS treatment, as well as the partial degrees of saturation achieved within the various regions of the sand specimen of Test 1.

5.6.3.1 Transport of solution: Test 1

Figure 5-16 shows summary plots of electric conductivity placed at approximate locations of the ten conductivity probes. More expanded versions of the plots are presented later in this section.

![Electric conductivity plots from Test 1](image)

Note: EC on the vertical axes denotes Electric Conductivity in mS/cm

Figure 5-16 Electric conductivity plots from Test 1
In Test 1, the IPS injection process was conducted in two days. During the first day, the injection was through the six PVC tubes (IT1 through IT6), and it took about 2.5 hours to complete. After this, surface injection started at IT7 (5 hours after zero time considered as the start of injection from the PVC tubes) and was completed at IT10 at about 7 hours from zero time. On the second day of injection, the remaining surface injections at IT11 through IT17 were completed at about 27 hours from zero time. In the electric conductivity plots shown in Figure 5-16, the dashed lines represent the night between first day and second day of injection when no data was recorded.

The electric conductivity plots shown in Figure 5-16 indicate that the chemical solution arrived at CP1, CP4, CP9, and CP10 during injection from the six PVC tubes (IT1 through IT6). These probes are close to the injection tips of the PVC tubes. CP5, CP7, and CP8 detected the arrival of the chemical solution during surface injection at IT7 through IT10. CP2 detected the arrival of the chemical solution during the second day surface injection at IT11 through IT17. Electric conductivity readings of CP3 and CP6 did not change during the injections leading to the conclusion that the chemical solution did not reach the locations of CP3 and CP6. This observation helped determine the zone of influence of the IPS treatment, as will be explained later in this section.

An effort was made to keep the concentration of the chemical solution during the injection close to 1%. The peak values of electric conductivity measured by the probes where the chemical solution reached were between 2.3 mS/cm and 3.5 mS/cm, very similar to values measure from the bench-top and glass tank tests. This electric conductivity values from the bench-top tests for 1% concentration were between 2.2mS/cm and 3.3 mS/cm, and from the glass tank tests were between 2.8mS/cm and 3.7mS/cm. It was concluded that the mixing and delivery system worked very well and was able to provide chemical solution with a steady concentration of 1%.

The electric conductivity plots shown in Figure 5-16 also show regions where the chemical solution did not reach and therefore the sand remained fully saturated. For example, the reading of CP3, which was located 14.5 feet (4.4 m) from the top of the specimen (within the bottom 1 meter), did not change during the injections, indicating that at this probe location, and most likely within the bottom 1 meter of the specimen, the
degree of saturation remained 100%. CP1 which was located about 12 feet (3.65 m) from the surface of specimen was the deepest probe that showed change in electric conductivity during injections from the PVC tubes indicating that the sand between 12 and 14.5 feet (3.65 to 4.4m) from the surface most likely was treated.

The electric conductivity of CP6 did not change during the injections. This fact can be explained by the relatively large lateral distances between CP6 and the injection tubes. It was concluded that, the mid-region of the sand specimen along close to south wall was not treated and degree of saturation remained 100%. Assuming symmetry, the mid-region close to the north wall was also not treated.

CP2 reading shows an increase in electric conductivity only after 25 hours from the start of the injections. This increase was attributed to arrival of chemical solution without any residual hydrogen peroxide (source of for gas generation). As was explained in Section 5.5, this was due to Mixing-Ion movement. But CP4 and CP7, which are 0.4m below and 0.7m above the location of CP2 were able to detect the arrival of the chemical solution with hydrogen peroxide during bottom and top injections. It was concluded that a thin layer of the sand specimen at the elevation of CP2 (2.6 m) from the surface of the specimen was not treated.

To study the zone of influence of the IPS treatment using the PVC injection tubes, the electric conductivity results (shown in Figure 5-16) and the horizontal distances of CP6 and CP9 from to the PVC injection tubes IT3 and IT6 (shown in Figure 5-17) are used. CP6 did not detect arrival of the chemical solution, and its smallest distance from an injection tube is 1.2m from IT3. CP9 detected the chemical solution and its largest distance from an injection tube is 0.6m from IT6. It is concluded that the radius of influence of injection from the PVC tubes was between 0.6 to 1.2 m.
During surface injection, efforts were made to inject the chemical solution close to the CPs located in the top 7 feet of the specimen. The jetting in of the surface injection tube significantly disturbed the sand specimen around the injection tube. Therefore, it was hard to make observations and conclusions regarding the zone of treatment by the surface injection.

5.6.3.2 **Degree of saturation: Test 1**

In Section 5.5 a typical electric conductivity plot was presented and explanations of how the recorded data was interpreted and ultimately the degree of saturation was computed at a conductivity probe location. In Figure 5-16, miniature versions of the electric conductivity plots of probes CP1 through CP10 were presented to help explain the transport of the chemical solution during the various stages of injection. In this section, expanded versions of the electric conductivity plots of each probe are presented to demonstrate how the degree of saturation was computed at each probe location.

Figures 5-18 through 5-27 present the expanded electric conductivity plots. Each figure shows the electric conductivity data and the location of the probe in plan and elevation, relative to the injection tubes. Along the top of the electric conductivity plot,
the time durations of the injections are shown to help interpret the recorded data. The dash line in the electric conductivity plot indicates the overnight break in data recording. The calculation of the degree of saturation at each probe location is also included in each probe figure.

Figure 5-18 presents the results for CP1.

\[ S = 100 \times \frac{B}{A} \times \frac{D}{C} = 57\% \]

From Figure 5-18, it is observed that the chemical solution arrived at the CP1 during the injections from the PVC tubes. During surface injection (after point D) small changes in electric conductivity was observed. These changes can not be due to arrival of new
solution as the probe was located far from the surface treated area, but can be explained by Mixing-Dilution and Mixing-Ion movement. CP1 detected the escape of bubbles during the night between the first and second days of injection (from point C to point D). The degree of saturation at CP1 was computed to be about 57%.

Figure 5-19 presents the results for CP2.

Figure 5-19 CP2 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 1
Figure 5-19 shows that the chemical solution did not reach CP2 during the first day of injection. It electric conductivity value during injection on the second day (surface injection) increased. This change in electric conductivity cannot be due to arrival of new solution containing hydrogen peroxide, because no significant decrease in electric conductivity was recorded, which would be sign of bubble generation in sand. In addition, CP2 was located far from the surface treated zone and the chemical solution could not have reached CP2. The increase in electric conductivity during the second day of injection can be explained by Mixing-Ion movement. The degree of saturation at CP1 was concluded to be 100%.

Figure 5-20 presents the results for CP3.

![Graph showing electric conductivity and degree of saturation for CP3]

Figure 5-20 CP3 electric conductivity and degree of saturation, Test 1

The chemical solution did not reach CP3 and the degree of saturation at that location remained 100%.

Figure 5-21 presents the results for CP4.
Two rises and drops in electric conductivity were recorded by CP4 during injection by the PVC tubes. The first rise in electric conductivity was due to arrival of chemical solution and subsequent drop is attributed to Mixing-Dilution. The second rise and drop were due to arrival of new solution and bubble generation, respectively. The first drop in electric conductivity cannot be due to bubble generation, because when solution arrived at the location of CP4 for the second time (second rise in electric conductivity value), electric conductivity value increased to 3mS/cm, which represents the electric conductivity of a sand saturated with 1% concentration of sodium per carbonate. It meant that when 1% solution arrived for the second time at the location of CP4 the
concentration of the solution in sand pores was less than 1% and the drop before arrival of solution for the second time was due to dilution. In other word, if the first drop were due to bubble generation, after the arrival of new solution of 1% concentration, no rise in electric conductivity should have been recorded, because the concentration of the solution in the sand pores would have already been 1%. Therefore, the second rise and drop in electric conductivity was used to calculate the degree of saturation of 88%. No significant changes in electric conductivity were observed at CP4 location during surface injection.

Figure 5-22 presents the results for CP5.

Figure 5-22 CP5 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 1
Figure 5-22 shows that the chemical solution arrived at CP5 during surface injection. The drop from the maximum electric conductivity is due to bubble generation. The small rise in electric conductivity following bubble generation is due bubble escape. Bubble escape continued overnight between the first and second days of injection. The degree of saturation at CP5 was computed to be about 83%.

Figure 5-23 presents the results for CP6.

![Figure 5-23: CP6 Electric Conductivity and Degree of Saturation, Test 1](image)

Figure 5-23 shows that the chemical solution did not reach CP6 and the degree of saturation at that location remained 100%.

Figure 5-24 presents the results for CP7.
At CP7, the chemical solution arrived during the first day of surface injection (IT7 through IT10). A very sharp drop in electric conductivity was observed in Figure 5-24 after the electric conductivity reached its peak value. This sudden decrease in electric conductivity happened in less than a minute and cannot be attributed to bubble generation, which takes time. A plausible explanation for this sharp drop is that when a surface injection tube is pulled out fast to avoid blow-out near the surface of the sand specimen, suction can be induced at the location of the CP bringing clean water and diluting the solution at the CP. Therefore, the sharp drop in electric conductivity can be
attributed to Mixing-Dilution. The more gradual decrease in electric conductivity past this sharp drop is due to bubble generation. During surface injection on the second day, no significant changes in electric conductivity were observed. The degree of saturation at CP7 was computed to be about 76%.

Figure 5-25 presents the results for CP8.

Figure 5-25 CP8 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 1

Figure 5-25 shows that the chemical solution reached at CP8 on the first day and during surface injection (IT7 to IT10). A sharp drop similar to CP7 was observed right after electric conductivity reached its peak value, which can be explained again by
Mixing-Dilution due to rapid pulling out of the injection tube. The gradual decrease in electric conductivity to point B is due to bubble generation.

The sudden drop followed by a sharp rise in electric conductivity observed in the plot (after point B) cannot be due to arrival of new solution nor bubble generation, which occur gradually, but can be explained by Mixing-Dilution and Mixing-Ion movement. The degree of saturation at CP8 was computed to be about 77%.

Figure 5-26 presents the results for CP9.

Figure 5-26 CP9 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 1
Figure 5-26 shows a number of rises and drops in electric conductivity that happened during injections from the PVC tubes. No significant changes happened during surface injections. It is very hard to differentiate between the peaks and drops at this CP location. The first rise and drop was due to arrival of new solution and generation of bubbles. However, the rest of the fluctuations are relatively fast and sudden and can be explained by Mixing-Dilution or ion movement. Some bubbles escaped from the specimen during the overnight hours. The degree of saturation at CP9 was computed to be about 84%.

Figure 5-27 presents the results for CP10.
At CP10, the chemical solution arrived during injections from the PVC tubes and was followed by a drop in electric conductivity due to bubble generation. The degree of saturation at CP10 was computed to be about 80%.

The electric conductivity data from CP1, CP5, and CP9 (Figures 5-18, 5-22, and 5-26) indicated escape of gas bubble especially after the injection was completed at the end of the first and second days. The pore void space created by escape of bubbles was filled with free water present above and immediately below the surface of the sand specimen. While other probes did not indicate bubble escape at the tips of the probes, loss of gas bubbles in the regions of other probes cannot be precluded.

The evaluation of the shaking test results in terms of benefits of IPS in liquefaction mitigation needed estimates of the degree of saturation within the sand specimen, in particular near where the pore water transducers were located. To obtain specimen-wide degree of saturation including the effect of gas bubble escape, measured volumes of inflow of the injected solution, outflow from the specimen, and infiltration of water back into the specimen filling the void spaces created by escaped bubbles were used. An average increase of 4% in degree of saturation S, due to bubble escape, was computed. This average increase in S was added to all computed S values from the conductivity probes that did not show bubble escape. Details of the computation of increase in S due to bubble escape can be found in the dissertation of Fritz Nababan.

Table 5-1 presents summary values of degree of saturation S without and with bubble escape. The first column in Table 5-1 shows the S values computed from the electric conductivity data of each probe, without using the increase due to bubble escape, if recorded. The second column shows the adjusted final values of S based on electric conductivity data that included increases due to bubble escape, if recorded (denoted with single asterisk), or values adjusted by adding 4% to the S values of probes that did not record bubble escape (denoted with double asterisk).
Table 5-1 Degree of saturation with and without gas bubble escape from Test 1

<table>
<thead>
<tr>
<th>CP #</th>
<th>Before Bubble, Escape (%)</th>
<th>Final degree of saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP1</td>
<td>49</td>
<td>57*</td>
</tr>
<tr>
<td>CP2</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>CP3</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>CP4</td>
<td>88</td>
<td>92**</td>
</tr>
<tr>
<td>CP5</td>
<td>78</td>
<td>83*</td>
</tr>
<tr>
<td>CP6</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>CP7</td>
<td>76</td>
<td>80**</td>
</tr>
<tr>
<td>CP8</td>
<td>77</td>
<td>81**</td>
</tr>
<tr>
<td>CP9</td>
<td>79</td>
<td>84*</td>
</tr>
<tr>
<td>CP10</td>
<td>80</td>
<td>84**</td>
</tr>
</tbody>
</table>

*: Based on CP analysis  
**: Based on Volume calculation

Figure 5-28 shows a summary of the calculated degree of saturation at the ten (10) electric conductivity probe locations for Test 1.

![Figure 5-28 Calculated degree of saturation including bubble escape, Test 1](image-url)
From the results shown in Figure 5-28, it is evident that the IPS treatment process adopted in Test 1 was not very effective. The six (6) PVC tubes with only their bottoms open but covered with geotextile were not capable of sending the chemical solution efficiently. The zone of influence for each tube was less than 1 meter. The surface treatment using an injection tube jetted into the top 2 meters and then slowly pulling it out while sending the chemical solution, appears to have been quite effective. The bottom 1 meter of the sand specimen remained fully saturated.

The electric conductivity probes were invaluable in monitoring the IPS process and evaluating the final saturation conditions of the sand specimen of Test 1. The results show: 1) top 2 meters of the specimen was partially saturated with S about 80-85%, 2) bottom 1 meter of the specimen remained fully saturate with S = 100%, and 3) middle section of the specimen was partially saturated with S ranging between 60 and 90%, except in the central region of the tank, where the sand remained fully saturated with S = 100%.

The conclusions regarding the partial saturation conditions of the sand specimen in Test 1 was confirmed by the shaking table test results, both observational and pore pressure data. Sand boils during or immediately after shaking of a loose saturated sand are indication of liquefaction of the sand. In Test 1, the shaking did not induce sand boils, on the surface of the specimen. Sand and water were ejected at isolated locations along the perimeter of the specimen next to the laminar tank walls, and at the locations of the steel wire meshes, indicating that there was liquefaction within the sand but most likely was at some depth. The high water pressure could escape upwards along the tank walls and the along the steel wire meshes that created easy paths for relieve of excess water pressures caused by liquefaction. In a way, Test 1 was a validation that if a sand is treated by IPS (such as the top portion of the specimen) it will have a much stronger resistance to liquefaction than the untreated sand (bottom 1 meter of the sand specimen), which in Test 1 liquefied under the applied shaking.
5.6.3.3 Effect of shaking on gas bubble escape: Test 1

Two days after completing the IPS treatment of Test 1, the laminar box was subjected twice to 15 cycles of 2Hz base excitation of about 0.1g. In both cases, evidences of liquefaction were observed in the form of sand and water ejections along the tank wall/sand boundaries, mainly on the west side of the box. Readings of the electric conductivity were made just before the first shaking and subsequently at the end of both shaking of the Test 1 specimen. The purpose of these readings was to explore if electric conductivity probes could provide information on potential loss of gas bubbles as a result of shaking of the specimen.

Figure 5-29 presents summary plots from the ten (10) conductivity probes.

Figure 5-29 Electric conductivity records showing data before and after shaking of sand specimen, Test 1
In each of the CP plots shown in Figure 5-29 there are four points. The triangular data points at time zero are the electric conductivity values recorded long after injections were completed and gas generation ceased. The first square data point at time zero is the reading taken about 48 hours after injection and gas generation were completed, and about 1.5 hours before the first shaking of the sand specimen. The second and third square data points are the electric conductivity readings taken immediately after the two shakings.

The electric conductivity data points shown in Figure 5-29 lead to the following observations and conclusions:

1. Comparisons of the electric conductivity data taken at the end of injection and bubble generation (triangular points) and just before the first shaking (square points) show only slight changes in the readings, except at CP3. Since during this 48-hour wait time there were no observations of bubbles escaping, these slight changes in electric conductivities at the nine CP locations are attributed to ion movements from higher to lower concentration regions. CP3 is located within the bottom 1 meter of the specimen, which was not treated and initially after injection had a reading of 0.2 mS/cm, a value corresponding to clean water and sand. The significant jump in the electric conductivity after 48 hours of wait period is unexplainable. The value of the electric conductivity just before shaking at CP3 is about 2.5 mS/cm, a value typical for sand with 1% sodium percarbonate solution. It appears that the solution from the treated region above CP3 made contact, possibly through the steel wire mesh within which CP3 was fixed.

2. Comparisons of the electric conductivity data before and after the two shakings show six CPs (CP2, CP4, CP5, CP7, CP8, and CP9) with no appreciable changes, while the remaining four CPs (CP1, CP3, CP6, and CP10) show significant changes.

3. The CPs that did not record changes in electric conductivity before and after the shaking, (CP2, CP4, CP5, CP7, CP8, and CP9) are in the IPS treated
zones. This indicates that gas bubbles were not lost due to the shaking. In fact, the visual observations made during and after each shaking confirmed this, because there were no evidences of gas bubbles escaping nor sand boils forming in the regions of these CPs. Therefore, IPS treated sand with $S = 80\%-90\%$ not only did not liquefy, but also did not lose any gas bubbles, even under large shaking that caused the untreated sand in the specimen to liquefy.

4. The electric conductivity readings of CP1, CP6, and CP10, increased because of the first shaking. This can be attributed to the liquefaction of the bottom 1 meter sand layer, which caused sand boils manifested on the surface of the specimen, mostly along the west side wall of the laminar box. Sand boils would have dramatically increased the void ratios of the sands at the tips of the conductivity probes (thus increasing the volume of the conductive fluid) leading to increase in electric conductivity. Electric conductivity of these three probes decreased due to the second shaking. This can be attributed to decrease in the void ratio, which was evident by the settlements observed at the surface mostly near the western region of the laminar box.

5. The electric conductivity of CP3 decreased because of both shaking. Again, this probe data is difficult to interpret. A possible reason for this decrease could be densification of the sand resulting smaller void ratio and decrease in electric conductivity. It is noted that the degree of saturation at CP3 was recorded to be 100%. Therefore, the sand at this location should have liquefied.
5.7 Electric conductivity results from laminar box Test 2

The electric conductivity readings of the ten (10) probes used in Test 1 clearly indicated that the IPS treatment of the sand specimen in Test 1 was limited to primarily the upper portion of the sand in the laminar box. This is the reason why, during the shaking of the specimen evidences of liquefaction were observed and recorded. The six PVC injection tubes were not effective in treating the entire sand specimen. Surface injection was employed in which an injection tube was jetted down to about 2 meters below the surface of the specimen and then slowly retrieved, while injecting the sodium percarbonate solution. The conductivity probe data showed that the IPS process of the sand specimen of Test 1 was partially effective, by reducing degree of saturation in some regions, while other regions remained fully saturated. Therefore, it was decided to repeat the laminar box test (Test 2) in which the entire sand specimen would be IPS treated using an injection tube jetted in from the surface of the specimen.

5.7.1 Specimen preparation: Test 2

In Test 2, twenty one (21) Milwaukee conductivity probes were used to monitor the IPS within the entire sand specimen. Thirteen CPs (CP1 through CP13) were fixed inside five steel meshes that also included pore water pressure transducers. As in Test 1, the steel meshes were hanged prior to placement of the sand from a steel truss fixed above the laminar box. The meshes were located in the southern region of the laminar box to allow placement of the sand from the norther side of the box.

Figure 5-30 shows the locations of the five (5) steel meshes and the first 13 conductivity probes. Additional eight (8) conductivity probes (CP14 through CP21) were also installed about 0.5m from the southern and northern walls of the box to ensure that the entire sand specimen from west to east and near the northern and southern walls could be monitored during the IPS process. These probes were individually held by their cables during the sand placement to ensure their desired locations within the specimen. Figure 5-30 shows the eight CPs along the northern and southern walls of the laminar box.
Figure 5-30 Plan and elevation views of the laminar box showing locations of electric conductivity probes, in Test 2
The procedure for the placement of the sand in the laminar box in Test 2 was identical to that followed in the preparation of Test 1 specimen. Mixture of Ottawa sand and water was pumped and rained inside the laminar box creating a very loose fully saturated sand specimen. Bucket samples were taken and relative densities were computed. It was concluded that both Test 1 and Test 2 sand specimens had very similar densities and void ratios.

5.7.2 IPS treatment: Test 2

IPS treatment of the sand specimen in Test 2 was done by jetting a 1.5 in diameter PVC injection tube down to about 1ft (0.3m) from the bottom of the laminar box. Figure 5-31 shows the closed-ended injection tube with the bottom 1 ft perforated to enhance horizontal injection of the chemical solution. Details of the tube and its use can be found in the dissertation by Fritz Nababan.

![Injection tube used to treat the sand specimen of Test 2](image)

The length of the tube used to reach to the bottom of the laminar box was about 17 feet long. Retrieving this tube slowly to treat the entire depth of the sand specimen would have been very difficult once the depth of treatment would reach near the surface of the specimen. Holding vertically a 17-ft (1.5-in diameter) PVC tube with most of its length extending above the surface of the sand while treating the near surface zone of the
specimen would have been impossible. Therefore, it was decided to conduct the IPS treatment in two stages. In stage 1, only the bottom 3m (10 feet) of the specimen would be treated using the 17-ft injection tube. Upon completion of the treatment of this lower zone, a shorter 7-ft injection tube was used to treat the upper 1.88m (6 feet) feet of the specimen.

The IPS treatment of the sand specimen was completed in 5 working days. The treatment of the lower 3m (10 feet) was completed in 3 days and of the surface 1.88m (6 feet) in 2 days. Figure 5-32 shows the zone of treatment during the first two days of injection. The treated zone was the bottom 3 meters of the specimen limited in the three quadrants in the North-South-West regions.

![Figure 5-32 IPS treatment zone during the first two days of injection](image1.png)

Figure 5-32 IPS treatment zone during the first two days of injection

Figure 5-33 shows the zone of treatment during the third day of injection. The treated zone was the bottom 3 meters of the specimen limited in the North-East quadrant region.

![Figure 5-33 IPS treatment zone during the third day of injection](image2.png)

Figure 5-33 IPS treatment zone during the third day of injection
Figure 5-34 shows the zone of treatment during the fourth day of injection. The treated zone was the top 1.88m (6 feet) of the specimen limited to the western half of the laminar box.

Figure 5-34 IPS treatment zone during the fourth day of injection

Figure 5-35 shows the zone of treatment during the fifth day of injection. The treated zone was the top 2m (6 feet) of the specimen limited to the eastern half of the laminar box.

Figure 5-35 IPS treatment zone during the fifth day of injection

As was mentioned earlier, IPS treatment was achieved by jetting 1.5-in diameter injection tube and then intermittently raising it at about 10 depths while pumping the chemical solution. The decision on the duration of injection at each depth was based on
the readings of the conductivity probes, making sure that the chemical solution reached at
one or more probes near the injection tube.

For the treatment of the bottom 3 meters (16 feet) a 17-ft long injection tube (IT)
was used at 13 different locations, as shown in Figure 5-36.

The first 5 locations were at the 5 steel meshes that held conductivity probes and
pore water pressure transducers. The other 8 locations were used to ensure that the entire
sand in the bottom 3 meters of the specimen got treated. The surface 1.88m of the
specimen was treated using 7-ft, injection tube IT at 19 different locations, as shown in
Figure 5-36.

Figure 5-36 Locations of injection tube for bottom treatment (IT1 through IT13) and for
surface treatment (IT14 through IT32), in Test 2

5.7.3 Electric conductivity results: Test 2

Electric conductivity measurements were made during the entire IPS treatment
process involving 32 injection locations. Readings of the 21 conductivity probes were
taken also just before and immediately after Test 2 sand specimen was shaken twice, in a similar way as in Test 1.

Analysis of the conductivity probe data was made to assess the transport of the chemical solution and to compute the partial degree of saturation induced by the chemical reaction that led to gas bubble generation within the pores of the sand.

### 5.7.3.1 Transport of solution: Test 2

Figure 5-37 shows summary plots of electric conductivity of probes CP1 through CP13. The plots are placed at the approximate locations of the probes within the specimen.
Figure 5-38 presents electric conductivity plots of probes CP14 through CP21. These eight probes were placed 0.5m from the north and south walls of the tank, to ensure that the IPS process treated the entire sand specimen of Test 2.

A number of observations can be made from the electric conductivity plots shown in Figure 5-37 and 5-38.

1. At the end of injection at 31 locations, all probes had recorded arrival of the chemical solution indicating that the entire sand specimen was treated.
2. Rises and drops in electric conductivity at probes distant from the injection location are attributed to Mixing-Dilution and Mixing-Ion movements.
3. When probes were near an injection location, they detected the arrival of solution in less than 10 to 15 minutes.

4. Probes that were less than 1m from an injection tube recorded the arrival of the solution. For example, at the time of injection from IT1, probes CP1, CP2, CP3, CP4, CP5, and CP19 (<1m from the injection location) recorded the arrival of the solution. Probes CP12, CP13, and CP18 (>1.3m from the injection location) did not detect the solution that was being pumped from IT1. It is noted that the duration of injection at a depth was controlled by the observation of arrival of the solution to the nearby conductivity probes. In the case of IT1, had the injection continued further the solution might have arrived at CP12, CP13, and CP18. In general, it was observed that a 15-minute injection was adequate to transport the solution about 1 meter away from the injection tube.

5. The peak values of electric conductivity measured by the probes ranged between 2.2 mS/cm and 4 mS/cm. This range from the laminar box Test 1 was 2.3 mS/cm and 3.5 mS/cm. From the bench-top tests, for a 1% concentration was between 2.2 mS/cm and 3.3 mS/cm. From the glass tank test, the range for 1% concentration was 2.8 mS/cm and 3.7 mS/cm. It appears that in the laminar box Test 2, the upper value of electric conductivity is slightly larger than that corresponding to 1% concentration solution as measured in all other tests. This indicates, that at times, the solution pumped in Test 2 may have had concentration as large as 1.2% (a value determined from bench-top tests described in Chapter 3).

5.7.3.2 Degree of saturation

In this section, expanded versions of the electric conductivity plots of each probe are presented to demonstrate how the degree of saturation was computed at each probe location. Figures 5-39 through 5-59 present the expanded electric conductivity plots. Each figure shows the electric conductivity data and the location in plan of the probe relative to the injection tubes. Along the top of an electric conductivity plot, the time duration of the injections are shown to help interpret the data. The dash lines in the
electric conductivity plots indicate long or overnight breaks in data recording. The calculation of degree of saturation at each probe location is also included in each plot.

Figure 5-39 presents electric conductivity plot of CP1. The data shows that the solution arrived at CP1 at the time of injection at IT1, which was very close to CP1. The rise in electric conductivity is due to arrival of ions from the solution. Subsequent drop is due to gas generation. The rise after gas generation is due to escape of bubbles from the tip of the conductivity probe. These changes in electric conductivity are very similar to what were recorded in Test 1. The large drop and slight rise on the second day of
injection was due to Mixing-Dilution and Mixing-Ion movement due to injections at IT2 to IT7 and not due to new solution because these injections were far from CP1. The degrees of saturation at CP1 before and after bubble escape were computed as 67% and 85%, respectively.

Before bubble escape:
\[ S = 100 \times \frac{\sqrt{B}}{A} \times \sqrt{\frac{D}{C}} = 64\% \]

After bubble escape:
\[ S = 100 \times 0.64 \times \sqrt{\frac{E}{D}} = 76\% \]

Figure 5-40 CP2 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-40 presents electric conductivity plot of CP2. Two rises and two drops were observed during injection at IT1. As mentioned before, bottom injection was conducted in 10 steps at 1-foot intervals. CP2 detected arrival of solution for the first time while injection was conducted at IT1, at a depth below that of CP2. A drop in
electric conductivity was observed after the first rise and can be explained by bubble generation. When injection from IT1 was at same depth as CP2, a second rise in electric conductivity was recorded followed by a drop due to bubble generation. The second rise might be due to slightly higher concentration of injected solution. Escape of bubbles was observed between first and second day of injection. During injection on the second day, abrupt rises and drops were observed in electric conductivity. These cannot be due to arrival of new solution and bubble generation as the changes were very sharp and sudden and injections conducted on the second day were far from CP2. The degrees of saturation at CP2 before and after bubble escape were computed as 64% and 76%, respectively.

Before bubble escape: \( S = 100 \times \frac{B}{A} = 85\% \)

After bubble escape: \( S = 100 \times 0.85 \times \frac{C}{B} = 95\% \)

Figure 5-41 CP3 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
Figure 5-41 presents electric conductivity plot of CP3. The solution arrived at CP3 during injection from IT1 and a drop due to bubble generation occurred after that. A very sharp drop after the rise in electric conductivity was due to pull out of the injection tube, which caused suction around the CP and therefore water diluted the arrived solution. A few more rises and drops were observed on other days of injections, which are attributed to Mixing-Dilution and Mixing-Ion movement.

\[ S = 100 \times \sqrt{\frac{B}{A}} = 81\% \]

Figure 5-42 CP4 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
Figure 5-42 presents electric conductivity plot of CP4. CP4 detected the arrival of solution when injection was at IT1. Bubble generation took place after electric conductivity reached its peak value. Other rises and drops in electric conductivity value were recorded during the second, third, fourth, and fifth day of injection, which are attributed to Mixing-Dilution and Mixing-Ion movement because the injection locations were far from CP4, and new solution could not have reached at the probe. In addition, the changes in electric conductivity were very abrupt and too sudden to be due to arrival of new solution or gas generation. The degree of saturation at CP4 was computed to be 81%.

\[ S = 100 \times \frac{B}{A} = 71\% \]

Figure 5-43 CP5 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
Figure 5-43 presents electric conductivity plot of CP5. The probe detected the arrival of solution during injection at IT2. The rises and small drops on the first injection day are attributed to Mixing-Ion movement. Therefore, it was assumed that degree of saturation at location of CP5 at the beginning of day two was 100%. During injection on the second day, solution arrived at CP5 when injection was at IT2. Gas generation followed, which reduced the electric conductivity from its peak value. During the third, fourth, and fifth day of injection no significant changes in electric conductivity were observed. The degree of saturation at CP5 was computed, based on changes in electric conductivity on the second day of injection, to be 71%.

Before bubble escape: \[ S = 100 \times \frac{B}{\sqrt{A}} = 80\% \]

After bubble escape: \[ S = 100 \times 0.80 \times \frac{C}{B} = 89\% \]

Figure 5-44 CP6 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
Figure 5-44 presents electric conductivity plot of CP6. The solution reached during injection from IT2, during the second day of injection, after which gas was generated. Overnight, gas bubbles escaped and conductivity increased slightly. Changes in electric conductivity at CP6 during the third, fourth, and fifth day of injection can be attributed to Mixing-Dilution and Mixing-Ion movement. The degrees of saturation at CP6 before and after bubble escape were computed as 80% and 89%, respectively.

\[ S = 100 \times \frac{B}{A} = 79\% \]

Figure 5-45 CP7 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-45 presents electric conductivity plot of CP7. The solution arrived during injection at IT4, and was followed by bubble generation. During injection at IT5, another rise and drop of electric conductivity were observed. This rise and drop cannot be due
to arrival of new solution and bubble generation because IT5 was located far from CP7. This change in electric conductivity can be explained by Mixing-Dilution and Mixing-Ion movement. Changes in electric conductivity during the third day of injection can be explained also by Mixing-Dilution and Mixing-Ion movement. The degree of saturation at CP7 was computed to be 79%.

\[
S = 100 \times \sqrt{\frac{B}{A}} = 59\%
\]

Figure 5-46 CP8 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-46 presents electric conductivity plot of CP8. CP8 detected the arrival of solution while injecting from IT3 at the same depth of CP8. A very sharp drop happened
after injection at IT3, which was due to pull out of the injection tube. This sharp drop was followed by a gradual drop, which can be explained by bubble generation. No significant changes were observed during the third, fourth, and fifth day of injection. The degree of saturation at CP8 was computed to be 59%.

Figure 5-47 CP9 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-47 presents electric conductivity plot of CP9. CP9 detected the arrival of solution during injection at IT3, and was followed by bubble generation. During surface injection on the fifth day of injection, a sharp drop was observed in electric conductivity, which was due to Mixing-Dilution. The degree of saturation at CP9 was computed to be 77%.
Figure 5-48 CP10 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-48 presents electric conductivity plot of CP10. CP10 detected the arrival of solution during injection at IT3. Arrival of solution was followed by a drop due to bubble generation. From the third day of injection and on the reading of electric conductivity at CP10 was erratic and not reliable. Because the injections on third, fourth, and fifth day were not close to CP10, it was assumed that during those injections there was no change in degree of saturation at CP10. The degree of saturation at CP10 was computed to be 76%, based on the measured electric conductivity at the time of the second day injection, before malfunctioning of CP10.

\[ S = 100 \times \sqrt{\frac{B}{A}} = 76\% \]
Figure 5-49 presents electric conductivity plot of CP11. The solution arrived at CP11 location during injection at IT3, and was followed by bubble generation. No significant changes were observed during the third, fourth, and fifth day of injection. The degree of saturation at CP11 was computed to be 77%.

$$S = 100 \times \frac{B}{\sqrt{A}} = 77\%$$

Figure 5-49 CP11 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-49 presents electric conductivity plot of CP11. The solution arrived at CP11 location during injection at IT3, and was followed by bubble generation. No significant changes were observed during the third, fourth, and fifth day of injection. The degree of saturation at CP11 was computed to be 77%.
Figure 5-50 CP12 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-50 presents electric conductivity plot of CP12. CP12 was able to detect the arrival of solution while injection was from IT5, on the second day of injection. The arrival of solution at CP12 was followed by bubble generation. Sudden rises and drops were observed in electric conductivity during bubble generation (from points B to D). Such sharp changes cannot be due to bubble generation. The second increase in electric conductivity could be due to arrival of new solution with higher concentration. The drops in electric conductivity from points A to B, and from points C to D were
considered due to bubble generation. Bubbles escaped during the second and third days of injection. The changes in electric conductivity after the third day of injection can be explained by ion movement due to diffusion. The degrees of saturation at CP12 before and after bubble escape were computed as 61% and 96%, respectively.

\[
S = 100 \times \frac{B}{\sqrt{A}} = 84\%
\]

After bubble escape:
\[
S = 100 \times 0.84 \times \frac{C}{B} = 100\%
\]

Figure 5-51 CP13 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-51 presents electric conductivity plot of CP13. CP13 was able to detect the arrival of solution while injecting from IT5. Two rises and drops in electric conductivity were observed. The second rise in electric conductivity happened while injecting from IT6, and cannot be due to arrival of new solution. In addition, the drop followed by the second rise is relatively sharp and cannot be due to bubble generation. Therefore, the
second rise and drop can be explained by Mixing-Dilution and Mixing-Ion movement. Significant amount of bubble escape was observed between the second and third day of injection. The changes in electric conductivity on the third day of injection cannot be due to arrival of new solution and can be explained by Mixing-Dilution and Mixing-Ion movement. The degrees of saturation at CP13 before and after bubble escape were computed as 84% and 100%, respectively.

\[ S = 100 \times \frac{B}{\sqrt{A}} = 81\% \]

Figure 5-52 CP14 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-52 presents electric conductivity plot of CP14. CP14 detected the arrival of solution while injection was from IT10. The distance between CP14 and IT10 was large, and no significant drop was observed after a large rise in electric conductivity, which indicated that arrived solution at CP14 did not have any hydrogen peroxide but contained
just sodium and carbonate ions. Therefore, it was concluded that the solution which arrived at CP14 location was not a new solution injected from IT10 and the change in electric conductivity on the third day of injection was due to Mixing-Ion movement. During the fourth day of injection, when injecting from IT18, which was close to CP14, a small rise followed by a drop in electric conductivity were observed (from point A to point B). These rise and drop are attributed to arrival of new solution and bubble generation. The degree of saturation at CP14 was computed to be 81%.

Before bubble escape: \[ S = 100 \times \frac{\sqrt{B}}{A} = 74\% \]

After bubble escape: \[ S = 100 \times 0.84 \times \frac{\sqrt{C}}{B} = 100\% \]

Figure 5-53 CP15 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
Figure 5-53 presents electric conductivity plot of CP15. CP15 was able to detect the arrival of solution injected from IT7. The rise in electric conductivity was followed by a drop, which was due to bubble generation. Bubble escape was observed between the second and third day of injection. Changes in electric conductivity were detected during the third, fourth, and fifth day of injection, which cannot be due to arrival of new solution, because the injections during those days were far from CP15. In addition, the drops were so sudden and abrupt that cannot be explained by bubble generation. These changes can be explained by Mixing-Dilution and Mixing-Ion movement. The degrees of saturation at CP15 before and after bubble escape were computed as 74% and 100%, respectively.

Before bubble escape: 
\[ S = 100 \times \sqrt{\frac{B}{A}} \times \sqrt{\frac{D}{C}} = 47\% \]

After bubble escape: 
\[ S = 100 \times 0.47 \times \sqrt{\frac{E}{D}} = 68\% \]

Figure 5-54 CP16 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
Figure 5-54 presents electric conductivity plot of CP16. The solution arrived at CP16 while injection was from IT11. The rise in electric conductivity was followed by a drop, which was due to bubble generation. During injection from IT12 which was far from CP16 small increase followed by a sharp drop in electric conductivity were observed. The drop was very abrupt and the conductivity decreased to 0.1 mS/cm, which represented the conductivity of sand saturated with clean water. These rise and drop were considered due to Mixing-Dilution and Mixing-Ion movement. During injection from IT13 a large rise followed by a gradual drop in electric conductivity was observed, which are attributed to arrival of new solution from IT13 and bubble generation. During the night between the third and fourth day of injection, rise in electric conductivity due to escape of bubbles was observed. During the fourth and fifth day of injection, no significant changes in electric conductivity were observed because injection locations were far from CP16. The degrees of saturation at CP16 before and after bubble escape were computed as 47% and 68%, respectively.
Figure 5-55 CP17 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-55 presents electric conductivity plot of CP17. The first increase in electric conductivity at CP 17 was during injection from IT7. This rise cannot be due to arrival of new solution because the injection point was far from CP17 and the rise in electric conductivity was not followed by a drop typical that associated with bubble generation. During injection from IT10, a second rise in electric conductivity was observed at CP17. This increase was due to arrival of new solution, and it was followed by a drop due to bubble generation. A very sharp drop before point A was due suction caused by the pull out of the injection tube, thus bringing in clean water or solution with lower concentration, thus diluting the solution at CP17. The sharp changes and fluctuations
after point B can be explained by Mixing-Dilution and Mixing-Ion movement. The degree of saturation at CP14 was computed to be 80%.

Figure 5-56 CP18 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-56 presents electric conductivity plot of CP18. CP18 was able to detect the arrival of new solution while the injection was from IT5. This increase in electric conductivity was followed by a drop, which was due to bubble generation. A sharp drop before point A was due to pull out of the injection tube. A rise between points B and C

Before bubble escape: \[ S = 100 \times \frac{B}{A} = 72\% \]

After bubble escape: \[ S = 100 \times 0.72 \times \frac{C}{B} = 100\% \]
can be explained by bubble escape during the second and third day of injection. The changes in electric conductivity during the third, fourth, and fifth day of injection cannot be due to arrival of new solution but can be explained by Mixing-Dilution and Mixing-Ion movement, because the changes were sudden and the injection points were far from CP18. The degrees of saturation at CP18 before and after bubble escape were computed as 72% and 100%, respectively.

Figure 5-57 CP19 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-57 presents electric conductivity plot of CP19. The first increase in electric conductivity at CP19 was due to arrival of sodium and carbonate ions (no hydrogen peroxide) from the first day injection from IT1. There was no gas bubble generation
because of lack of hydrogen peroxide. The changes in electric conductivity at CP19, during subsequent injections were very sudden and rises were so abrupt that it was not possible to distinguish the bubble generation section of the plot. Therefore, degree of saturation at CP19 was not calculated.

Figure 5-58 presents electric conductivity plot of CP20. CP20 detected the arrival of solution while injection was from IT2. This was followed by a drop in electric conductivity, which was due to bubble generation. Sharp rises and drops were observed by CP20 after point B on the second, third, fourth and fifth day of injection. These rises

\[ S = 100 \times \frac{B}{A} = 84\% \]

Figure 5-58 CP20 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2
and drops cannot be due to bubble generation and are attributed to Mixing-Dilution and Mixing-Ion movement. The degree of saturation at CP20 was computed to be 84%.

Figure 5-59 CP21 electric conductivity, probe location relative to injection tubes, and degree of saturation, Test 2

Figure 5-59 presents electric conductivity plot of CP21. CP21 detected the arrival of solution while injection was from IT8. Because of the large distance between CP21 and IT8, this change in electric conductivity is attributed to Mixing-Dilution and Mixing-Ion movement. The changes in electric conductivity on the fourth and fifth day of injection was so abrupt that it was not possible to distinguish the arrival of new solution and bubble generation. Because of these difficulties in interpreting the data, the degree of saturation at CP21 was not calculated.

Degree of saturation based on measured electric conductivity values was calculated and presented for each probe location in Figures 5-39 through 5-59. The effect of bubble
escape in calculating degree of saturation was included for all the conductivity probes that detected bubble escape (CP1, CP2, CP3, CP6, CP12, CP13, CP16, and CP18). Bubbles escaping was observed mostly near the steel meshes and jetted injection tube locations. Figure 5-60 shows the bubbles escaping when the injection was over.

![bubbles escaping](image)

Figure 5-60 Escaping gas bubbles observed at the surface of the sand specimen of Test 2

As mentioned in Section 5.6.3.2, if a conductivity probe did not detect bubble escape, it meant that there was no bubble escape at the tip of the probe, but bubbles could have escaped from the region around the probe. To estimate the average increase in degree of saturation in the various regions of the sand specimen due to gas bubble escape, the measured volumes of inflow and outflow of the chemical solution, as well as the volume of water that infiltrated back into the specimen due to escaped bubbles were used. The details of the calculations of the average increase in degree of saturation can be found in the dissertation of Fritz Nababan.

Table 5-2 presents a summary of the degree of saturation for each probe location. The first column in the table presents the degree of saturation computed using the electric conductivity data, without considering gas bubble escape. The second column in the table summarizes the degree of saturation including bubble escape. If a conductivity probe recorded bubble escape, degree of saturation was estimated based on analysis of the probe data. If a conductivity probe did not indicate bubble escape, the degree of saturation from that probe was increased to account for the general increase in the degree of saturation of the specimen due to bubble escape, as observed by loss of volume of solution back into the specimen.
Table 5-2 Degree of saturation with and without gas bubble escape from Test 2

<table>
<thead>
<tr>
<th>CP #</th>
<th>Before Bubble Escape</th>
<th>After Bubble Escape</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP1</td>
<td>67</td>
<td>85*</td>
</tr>
<tr>
<td>CP2</td>
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<tr>
<td>CP10</td>
<td>76</td>
<td>94**</td>
</tr>
<tr>
<td>CP11</td>
<td>77</td>
<td>87**</td>
</tr>
<tr>
<td>CP12</td>
<td>61</td>
<td>96*</td>
</tr>
<tr>
<td>CP13</td>
<td>84</td>
<td>100*</td>
</tr>
<tr>
<td>CP14</td>
<td>81</td>
<td>88**</td>
</tr>
<tr>
<td>CP15</td>
<td>74</td>
<td>100*</td>
</tr>
<tr>
<td>CP16</td>
<td>47</td>
<td>68*</td>
</tr>
<tr>
<td>CP17</td>
<td>80</td>
<td>90**</td>
</tr>
<tr>
<td>CP18</td>
<td>72</td>
<td>100*</td>
</tr>
<tr>
<td>CP19</td>
<td>CP data not reliable</td>
<td></td>
</tr>
<tr>
<td>CP20</td>
<td>84</td>
<td>100**</td>
</tr>
<tr>
<td>CP21</td>
<td>CP data not reliable</td>
<td></td>
</tr>
</tbody>
</table>

*: Based on CP analysis
**: Based on volume calculation
Figure 5-61 shows a summary of the calculated degree of saturation placed at approximate locations of the conductivity probes in the sand specimen of Test 2.

The degree of saturation results show that, except at a few locations, most of the sand specimen of Test 2 was partially saturated. The average degree of saturation within the top 1.88m (6 feet) of the specimen was about 90%. The average degree of saturation within the bottom 3m (10 feet) of the specimen was about 91%.

The fact that after twice shaking the sand specimen of Test 2, there were no observations of sand boils or sand and water ejections, confirmed that the specimen was indeed partially saturated.
5.7.3.3 Effect of shaking on gas bubble escape: Test 2

A day after completing the IPS treatment of Test 2, the laminar box was subjected twice to 15 cycles of 2Hz base excitation of about 0.1g. Readings of the electric conductivity were made just before the first shaking and subsequently at the end of both shaking of the Test 2 specimen. Again, the purpose of these readings was to investigate the potential loss of gas bubble from the IPS treated specimen due to shaking. It is noted that at no time during and after the two shakings of the sand specimen of Test 2, there was any evidence of liquefaction.

Figure 5-62 presents summary plots of electric conductivity readings of CP1 through CP13, taken before and after the two shakings of the sand specimen of Test 2.

Figure 5-62 Electric conductivity records of probes CP1 through CP13, before and after shaking of sand specimen, Test 2
Figure 5-63 presents summary plots of electric conductivity readings of the probes placed along the north and south boundaries of the laminar box (CP14 through C21), taken before and after the two shakings of the sand specimen of Test 2.

Figure 5-63 Electric conductivity records of probes CP14 through CP21, before and after shaking of sand specimen, Test 2

In each of the CP plots shown in Figures 5-62 and 5-63 there are four points. The triangular data points at time zero are the electric conductivity values recorded long after injections were completed and gas generation ceased. The first square data point at time zero is the reading taken about 24 hours after injection and gas generation was completed, and before the first shaking of the sand specimen. The second and third square data points are the electric conductivity readings taken immediately after the two shakings.
The electric conductivity data points shown in Figures 5-62 and 5-63 lead to the following observations and conclusions:

1. At all probes, the electric conductivity readings from end of injection to just before the first shaking, (24 hours of wait time) did not change appreciably. This indicates that there were no gas bubble escape and the degree of saturation of the specimen remained unchanged.

2. Except at CP9 and CP11, no significant changes in electric conductivity were observed during and after both shakings of the specimen. Therefore, there were no bubble movement or escape due to the shaking.

3. At CP9, increases in electric conductivity were recorded after both shakings. Because no sand boils nor other evidences of liquefaction were observed, these increases cannot be attributed to gas escape. A likely explanation is that increases in pore water pressures due to both shaking could have induced flow of high ion concentration solution towards the CP9 location.

4. At CP11, decrease in electric conductivity was observed because of the first shaking. A likely explanation can be that clean water or solution with low concentration of ions, could have flowed towards CP11, again induced by increases in pore water pressures because of the shaking.

5. The conductivity probes located about 0.5m from the north and south walls of the laminar box did not show appreciable changes due to the shakings. This is indicative that there was no liquefaction or gas bubble loss, as was the case in Test 1, especially along the tank walls. The visual observations of no sand boils or sand-water ejections anywhere including along the tank walls made in Test 2 are consistent with the electric conductivity data of CP14 through CP 21.

5.8 Summery and conclusions

Electric conductivity probes were used in the implementation of Induced Partial Saturation (IPS) in the laminar box of NEES@Buffalo, at the State University of New
York in Buffalo. Two tests (Test 1 and Test2) were conducted, which differed only in the process of inducing partial saturation in the sand specimens. The purpose of the laminar box tests was two folds: 1) to evaluate the IPS process and equipment designed to reduce degree of saturation of a large sand specimen, under representative field conduction and 2) to evaluate the effectiveness of IPS as a liquefaction mitigation measure, by shaking the IPS treated specimens employing the shaking table upon which the laminar box rested.

Electric conductivity probes were used extensively to monitor the IPS process, and to determine the partial degree of saturation of the specimens and its spatial distribution. The tests also created opportunities to demonstrate many benefits of using conductivity probes in the implementation of IPS.

The following observations and conclusions are drawn from analyses of the electric conductivity data from the two laminar box tests:

1. The Milwaukee conductivity probes with extended cables functioned extremely well under rough and long-term conditions.
2. Zone of IPS treatment can be determined by observing the arrival of the chemical solution at the probe locations.
3. IPS process in terms of making decisions about injection location, pressure, and injection duration can be established by monitoring the probe readings and observing the arrival or not of the chemical solution.
4. Zones where treatment was not effective or could not be reached can be identified and alternative or additional injection procedures can be implemented, to ensure treatment of an entire specimen.
5. Degree of saturation can be determined at each probe location, providing crucial data needed in the interpretation of the effectiveness of IPS as liquefaction mitigation.
6. Probes can detect gas escape from the sand specimen, and provide estimates of final degree of saturation that includes the effect of gas escape.
7. Specimens or regions of specimens that the probes indicated were partially saturated, did not liquefy during large enough shaking under which a fully saturated specimen liquefied. The partial saturation conditions determined by the probes were confirmed by the shaking table responses of the specimens.

8. Effects of dilution and ion movements can be detected by the probes.

9. Probes can be used to determine the rate of chemical reaction and hence the time duration within which the injection needs to be completed before significant gas bubbles are generated.

10. Probe readings can provide estimate of the concentration of the chemical solution reaching the pores of the sand, at a probe location.
Chapter 6

Use of Electric Conductivity Probes for Monitoring IPS in Pilot Field Test at Wildlife Liquefaction Array (WLA)

6.1 Overview

Chapter 5 described implementation of IPS in two large sand specimens prepared in the laminar box of NEES@Buffalo. In the laminar box tests, use of electric conductivity probes was beneficial in monitoring the transport of the chemical solution in the sand specimens and in estimating degree of saturation. In addition, as part of this larger research project, IPS was implemented in the field at the Wildlife Liquefaction Array (WLA) of NEES@UCSB, in Brawley, California. The field test involved treating with IPS a silty sand layer 2mx2m in plan area, it was then instrumented with pore pressure transducers and geophones, and shaken using the T-Rex vibratory truck of NEES@UT from the University of Texas at Austin. The purpose of the field research was to evaluate the beneficial effect of IPS on liquefaction. Details of the field IPS implementation and ground shaking results are presented in an upcoming dissertation by Fritz Nababan.

Three trips were made to the WLA to evaluate the site conditions, and to identify the location and prepare the plan for the final test.

Trip 1: January 23\textsuperscript{rd} to February 4\textsuperscript{th}, 2014

Trip 2: March 3\textsuperscript{rd} to March 18\textsuperscript{th}, 2014

Trip 3: May 20\textsuperscript{th} to July 25\textsuperscript{th}, 2014

The first two trips were exploratory with the purpose of learning about the site conditions, soil characteristics, appropriate procedure for installing injection tubes, and quality of the river and ground water and its suitability for IPS implementation. During the third trip, a pilot field IPS test was performed using an injection and an extraction tube,
and conductivity probes. The primary purpose of the pilot test was to determine the size of the zone of partial saturation, under the actual field conditions. This information was then used to prepare the IPS implementation plan at the full-production site, (the 2mx2m area).

This chapter presents relevant details and knowledge gained from the two exploratory trips, as well as the details and results of the pilot test conducted during the third trip to WLA.

6.2 Introduction to Wildlife Liquefaction Array (WLA)

The NEES@UCSB Wildlife Liquefaction Array (WLA) is a research field site funded by the National Science Foundation, and monitored and maintained by Dr. Jamison Steidl from the University of California at Santa Barbara. The site is located 13 km north of Brawley, along the western shore of the Alamo River, in the Imperial Valley of California. The site is near the southern end of the San Andreas Fault and has experienced large earthquakes that have caused widespread liquefaction in the region and at the site. The NEES/NSF IPS research had a budget and plan to utilize the site and conduct research in collaboration with Dr. Jamison Steidl, from UCSB, Dr. Leslie Youd, formerly of Brigham Young University, and Dr. Kenneth H. Stokoe from the University of Texas at Austin.

Figure 6-1 shows Google Earth photographs of the location of the NEES@UCSB WLA site. Included in the figure are the locations of the NEES@UCSB and USGS instrumented sites that monitor potential liquefaction during regional earthquakes, as well as the location of the IPS research final test site conducted during the third trip to WLA.
Figure 6-1 Locations of WLA, NEES@UCSB, USGS, and IPS field test sites
Figure 6-2 shows the locations of the three sites where the IPS research project team conducted exploratory (first and second trips) and final tests (third trip).

![Figure 6-2 Locations of IPS field test sites](image)

6.3 Summary of findings from the first and second trips

During the first two trips, exploratory tests were conducted to evaluate the general site conditions, the challenges that are present with regards to site accessibility, supply of water and its quality, type of injection tube to use and the proper installation procedure to follow, and the adequacy of the chemical solution preparation and delivery system. Details of the findings and knowledge gained in all these explorations are presented in the dissertation of Fritz Nababan.

This section focuses on presenting knowledge gained in three areas (site condition, injection tube installation, and river and ground water quality) that were relevant to the use and implementation of conductivity probes in the pilot test conducted during the third trip.
6.3.1 Site condition

The site condition, layer stratification, and soil properties have been investigated extensively by Drs. Steidl and Youd, CO-PIs of the NEES@UCSB research grant by NSF. This information was made available to the IPS research investigators. Selected wash borings and SPT test made at the three IPS sites confirmed the general stratigraphy and type of soils encountered at the WLA site. The most relevant variability was found to be in the depth to the liquefiable soil layer consisting of silts and silty sands.

Figure 6-3 shows an idealized soil column that depicts the typical stratification at the IPS research site.

![Idealized soil column showing the various soil layers at the IPS test site](image)

The soil profile at the final IPS test site consisted of about 9-ft thick layer of low to high plasticity clay. Below this clay, there is a thin silt layer of about 1 ft in thickness. Below the silt is a deep deposit of a silty sand layer. The silts and the silty sands have liquefied during past regional earthquake. The IPS research targeted the silty sand layer
for investigations, recognizing that the thin silt layer would be difficulty to locate and treat with precision. It was hoped that while treating the silty sand layer, the treatment would extend also to the silt layer. Further details on the site condition and IPS treatment of the layers are presented in the dissertation of Fritz Nababan.

6.3.2 Injection/extraction tube installation methods

It is noted that all field operations were conducted without the benefit of large mechanized drilling equipment. Therefore, two alternative methods of installing injection or extraction tubes were explored, namely, by jetting the tube into the ground, or by driving the tube (open-ended or closed but with side perforations) and then washing the inside of the tube to prepare for injection/extraction. In addition, it was determined that unlike a galvanized steel tube, a PVC tube can be handled with ease, sized to desired length, perforated, and driven without breakage. Therefore, PVC tubes were used in all the field operation at the WLA site. Figure 6-4 represents two methods of installation of injection/extraction tube, jetting the tube into the ground and driving the tube and then washing inside the tube.

![Installation of Injection tube](image)

Figure 6-4 Installation of Injection tube by a) jetting metal tube and b) driving and then washing inside the PVC tube

While jetting a tube was relatively easy, the process loosened up the soils around the tube to the extent that the injected solution had a preferred path
flowing upwards from around the tube. This problem was avoided by driving closed-ended. Driving even an open-ended tube was acceptable, because of a clay plug formed at the tip while driving. Based on these experiences, it was decided to drive PVC tubes for injection or extraction purposes.

6.3.3 River and ground water quality

Two sources were available at the site to provide water for preparing sodium per carbonate solution. Pumping of water from the Alamo River, flowing only a few feet from the site, and pumping ground water which was about 5 feet below the ground surface, were both utilized. It was observed that both river water and ground water contained silts and were quite contaminated. The silt content of the ground water was significantly less than that of the river water. It was decided that the river water would be used to clean equipment and clean water storage and supply barrels. Ground water would be used to wash inside the injection tubes and to prepare the chemical solution. Electric conductivity of river water and ground water were measured to range between 2.8 mS/cm and 3.3 mS/cm. Electric conductivity of both ground water and river water were higher than regular water (0.1 to 0.2 mS/cm), a clear indication of presence of ions from contaminants.

Tetra Tech, INC. and Wetlands Management Services has published a report summarizing the quality of the Alamo River. The report was prepared in 2007 for the Wildlife Conservation Board and Salton Sea Authority. Table 6-1 represents some of the laboratory tests results on the Alamo River water.
Table 6-1 Water quality of Alamo River

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Coliform (mpn/100 ml)</td>
<td>4.6x10^5</td>
</tr>
<tr>
<td>Sulfate (mg/l)</td>
<td>880</td>
</tr>
<tr>
<td>Nitrate-N (mg/l)</td>
<td>8.1</td>
</tr>
<tr>
<td>Nitrate (mg/l)</td>
<td>0.3</td>
</tr>
<tr>
<td>Ammonia-N (mg/l)</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen (mg/l)</td>
<td>1.3</td>
</tr>
<tr>
<td>Ortho-Phosphate (mg/l)</td>
<td>0.31</td>
</tr>
<tr>
<td>Total Phosphorus (mg/l)</td>
<td>0.69</td>
</tr>
<tr>
<td>Total Suspended Solids</td>
<td>290</td>
</tr>
<tr>
<td>Total Selenium (µg/l)</td>
<td>5.94</td>
</tr>
<tr>
<td>Dissolved Selenium (µg/l)</td>
<td>5.21</td>
</tr>
<tr>
<td>Selenite (SeIV) (µg/l)</td>
<td>0.111</td>
</tr>
<tr>
<td>Selenate (SeVI) (µg/l)</td>
<td>0.73</td>
</tr>
<tr>
<td>Organic Selenium (mg/l)</td>
<td>0.51</td>
</tr>
<tr>
<td>Dissolved Oxygen (mg/l)</td>
<td>11.6</td>
</tr>
<tr>
<td>PH</td>
<td>7.65</td>
</tr>
<tr>
<td>Electrical Conductivity (µS/cm)</td>
<td>2975</td>
</tr>
<tr>
<td>Oxidation Reduction Potential (mV)</td>
<td>190.4</td>
</tr>
</tbody>
</table>

The study on Alamo River water by Tetra Tech, INC. and Wetlands Management Services confirms the fact that Alamo River water contains many ions such as Sulfate, Nitrate and Phosphate, which are responsible for the high electric conductivity readings made by the conductivity probes. Because the quality of the ground water was far different from the regular water used in the laboratory bench top tests, there was a need to study the effect of the various ions present in the WLA ground water on the rate of reaction of Sodium percarbonate. This would also help in the decision whether the WLA ground water would be suitable to use in the preparation of the chemical solution to be injected at WLA field site. Samples of ground water and sand from WLA site were shipped to Northeastern University and tested in the laboratory in the same way as the bench-top tests that were described in Chapter 3.

The electric conductivity of the ground water specimens, which were taken to the lab was same as the one measured at the site (~3 mS/cm). Therefore, it was concluded that the samples were representative of the field ground water condition. Specimens of solution
(no sand) with regular water and ground water were prepared to observe visually differences in the generation of gas bubbles. In addition electric conductivity and PH of the prepared specimens were measured. Table 6-2 represents the measurements of electric conductivity and PH for prepared specimen.

Table 6-2 Comparison of test results on regular water and ground water from WLA

<table>
<thead>
<tr>
<th></th>
<th>Chemical Concentration (%)</th>
<th>PH</th>
<th>Conductivity (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular water</td>
<td>-</td>
<td>8.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Ground water</td>
<td>-</td>
<td>7.94</td>
<td>3.3</td>
</tr>
<tr>
<td>Solution with tap water (RW)</td>
<td>2.2</td>
<td>10.8</td>
<td>19.8</td>
</tr>
<tr>
<td>Solution with ground water (GW)</td>
<td>2.2</td>
<td>10.38</td>
<td>23.6</td>
</tr>
</tbody>
</table>

Table 6-1 shows that the approximately 3 mS/cm difference in electric conductivity between regular water and ground water remained the same in 2.2% concentration of solution, leading to the conclusion that the difference in the electric conductivity of regular and ground water is primarily due to presence of the various contaminant ions in the ground water. Figure 6-5 shows comparisons of two vials with 2.2% chemical solution indicating visual determination of similar generation of gas bubbles in tap and ground water specimens. Therefore, the presence of the contaminant ions did not hinder the reaction of Sodium percarbonate leading to gas generation.
Figure 6-5 Sodium percarbonate solution in tap water and ground water and visual observation of generation of gas bubbles (2.2% concentration)

A small specimen of WLA sand saturated in 2.5% concentration of sodium percarbonate and WLA ground water solution was prepared to study the generation of gas bubbles in WLA sand. The specimen was prepared by placing a conductivity probe in a beaker containing a certain amount of chemical solution having 2.5% concentration and then raining WLA sand in the beaker. The electric conductivity of the prepared solution was 26.3 mS/cm. The electric conductivity of the sand specimen saturated with the solution was measured at different time intervals. Figure 6-6 presents the prepared specimen.
Figure 6-6 WLA sand saturated in 2.5% concentration of the Sodium percarbonate solution with ground water from WLA.

Figure 6-7 represents the electric conductivity data measured during the test.

![Electric conductivity probe](image1)

Free water at the beginning of the test

![Electric conductivity probe](image2)

Figure 6-7 Electric conductivity in WLA sand in chemical solution prepared with WLA ground water

It can be observed from Figure 6-7 that the maximum value of electric conductivity of the specimen (at t=0, the time when the sand was rained in the beaker) was 2.7 mS/cm. It is noted that from the bench-top tests on specimens of Ottawa sand in clean water, peak electric conductivity value of 4.2 mS/cm was recorded for chemical concentration of 1.5%.
The electric conductivity of the WLA specimen with 2.5% concentration, and having the contaminant ions of the ground water is surprisingly smaller (2.7 mS/cm) than that of 1.5% concentration Ottawa sand specimen with clean water (4.2 mS/cm). This lower peak value of electric conductivity can be explained by high tortuosity of the silty sand from WLA compared with the uniformly graded Ottawa sand.

Tortuosity relates to the nature of the void paths that electrons need to travel in a saturated granular medium. High tortuosity signifies a difficult path for electrons to travel in the medium from one electrode to the other one and therefore results in smaller electric conductivity value. Figure 6-8 represents the schematic drawing of the tortuosity and the path through which electrons need to travel.

![Figure 6-8 Schematic drawing of sand with high and low tortuosity](image)

In Figure 6-8 two sand specimens with high and low tortuosity are presented. The high tortuosity sand is a well graded, whereas the low tortuosity sand is uniformly graded. The lines on the figures represent the expected paths for the electrons to travel. It is observed that in a specimen with higher tortuosity electron will have longer path to travel and therefore will have lower electric conductivity. In addition, as was described in Chapter 2, Archie’s law indicates that electric conductivity is in inverse relation with tortuosity of sand. Therefore, the higher the tortuosity of sand specimen the lower the electric conductivity of the specimen would be.

Based on the above discussion, recognizing that the silty sand from the WLA is a well graded medium than the uniform Ottawa sand, the lower electric conductivity of the WLA silty sand compared with the Ottawa sand is attributed to higher tortuosity.

Figure 6-7 shows decrease in electric conductivity as a result of gas generation in the void spaces of the WLA sand specimen. This specimen was prepared using WLA ground
water, which has contaminant ions. The investigations on the rate of reaction that were reported in Chapters 3 and 5 were conducted using Ottawa sand and clean water (Chapter 3) and solution with clean water (Chapter 5). It was important to evaluate any potential effect of the ions present in the ground water on the rate of reaction results reported in Chapters 3 and 5.

To evaluate the effect of the contaminant ions present in the WLA ground water on the rate of reaction in just the solution before injecting it into the WLA sand, the test reported in Chapter 5 was repeated but this time using the WLA ground water. Figure 6-9 presents a comparison of the rates of reaction of solution in WLA groundwater and in clean regular tap water.

![Graph showing comparison of rates of reaction in WLA groundwater and in clean regular tap water](image)

Figure 6-9 Rate of reaction in WLA ground water and in clean regular water for 1% concentration

Based on the comparison made in Figure 6-9, it is concluded that the use of contaminated water of WLA accelerates the reaction during mixing, prior to injection. However, the amount of gas lost during a typical 20 minutes of mixing and preparation of the solution is about 4% (0.05/1.3) of the total yield of the chemical reaction.

To study the rate of generation of gas bubbles in WLA sand and ground water, a bench-top test similar to the one explained in Chapter 3 was prepared with 1% concentration of sodium percarbonate solution. Figure 6-10 represents the set-up of the bench-top experiment.
Figure 6-10 Bench-top experiment with WLA sand and 1% concentration of sodium percarbonate solution with ground water from WLA.

Figure 6-11 shows measured electric conductivity as well as calculated degree of saturation recorded from the test on WLA sand and ground water specimen. The results are compared with the test results on a specimen prepared with Ottawa sand and 1% concentration of sodium percarbonate solution in regular water.

Figure 6-11 shows that the initial electric conductivity reading in chemical solution with ground water and WLA sand was 1.9 mS/cm, which was smaller than chemical solution with regular water and Ottawa sand (2.7 mS/cm). As it was explained in previous test high tortuosity of the WLA sand is the reason for this smaller peak electric conductivity value in specimen with WLA sand and 1% concentration of solution with ground water.
Figure 6-10 also shows that in the WLA specimen, the rate of decrease in electric conductivity due to gas generation was faster than in the Ottawa sand specimen. In addition, the final degree of saturation in the WLA specimen was about 73%, which was higher than that of the Ottawa sand (60%). It was concluded that the tortuosity of the WLA sand and the contaminant ions in the WLA ground water have an accelerating effect on the rate of the chemical reaction, leading to slightly higher degree of saturation than expected based on Ottawa sand and regular clean water. This was another challenge that was faced in the field research of implementation of IPS at WLA site.

Another observation that was made from the field investigations conducted during the second trip to the WLA site was that the conductivity probes were at times unable to detect the arrival of the chemical solution, when expected to do so. To investigate the travel time of the chemical under a large hydraulic gradient (8"-5" of head difference), a simple test was performed in the field. An open-ended PVC tube was installed with its tip inside the silty sand layer. The inside of the tube was cleaned by washing. A Milwaukee conductivity probe was then pushed 7.5 cm into the silty sand deposit. The tube was then filled with a chemical solution with 1% concentration. Surprisingly, the conductivity probe after 15 minutes did not detect the arrival of the chemical solution, as it penetrated the sand. The reason for this observation was investigated in the laboratory.

A laboratory WLA sand specimen (10.6 cm long) saturated with WLA ground water was prepared in a Plexiglass column. A Milwaukee conductivity probe was then pushed 7.5 cm into the specimen. A 1% concentration chemical solution prepared with WLA ground water was then poured on top of the specimen and the height of the solution above the top of the specimen was maintained at 10.2 cm. Figure 6-12 shows the set-up of the simulation of the field test that was performed to observe travel distance of the chemical solution at the WLA site.
Figure 6-12 Test setup for simulating the field test conducted to test ability of a pushed conductivity probe to detect the arrival of chemical solution

Immediately after pouring the chemical solution on top of the specimen, the electric conductivity of the outflow was recorded at different time intervals. At the same time, the electric conductivity reading of the pushed conductivity probe was recorded periodically.

Figure 6-13 shows the electric conductivity of the solution collected from the outflow.

Figure 6-13 Electric conductivity of solution collected from outflow

The electric conductivity at the outflow started at 2.9 mS/cm, the value corresponding to the WLA ground water, without the chemicals solution. About 10 minutes after the start of the test, electric conductivity of the outflow started to increase, indicating the arrival of ions from the chemical solution. After about 175 minutes, the electric conductivity of the
outflow reached 12 mS/cm, which is the value for the 1% chemical solution that was being sent from the top of the specimen. It was concluded that under the hydraulic head difference of 10.2 cm, the full concentration of the chemical solution traveled 10.6 cm. During that time, the electric conductivity at the probe location (7.5 cm below the top of the specimen) was also recorded.

Figure 6-14 shows the electric conductivity measured at the conductivity probe location, inside the specimen.

![Electric conductivity measured inside the specimen, 7.5 cm from top of the specimen](image)

Electric conductivity at the tip of the conductivity probe inside the sand specimen started to increase after 90 minutes from the beginning of the test, which is quiet long compare to the arrival time of the chemical solution in the outflow (10 minutes). The delay in increase of electric conductivity read by the probe in the specimen can be explained by fact that the probe has two protruding electrodes and was pushed into the specimen. The reading from the probe is that of the sand/fluid present between the two electrodes. When the probe is pushed in an initially WLA silty sand and ground water (no chemical solution), mixture a pocket of the specimen probably was trapped between the two electrodes and pure vertical flow of the chemical solution could not replace the trapped ground water until after 90 minutes. It is also observed that diffusion and ion mixing were not dominant for at least the first 90 minutes of the test.

The laboratory test described above led to the conclusion that 1) because of the presence of silts in the sand, which reduces the permeability of the sand, the travel time of the chemical solution is slow (90 minutes to travel 10.6 cm under a downward gradient of
20.8/10.8 = 1.9) and 2) installation of a Milwaukee probe into sand by pushing renders the probe ineffective, for all practical purposes.

In summary, various tests were conducted to evaluate the quality of the Alamo River and ground water at the WLA site. Conductivity probes were invaluable in evaluating the suitability of the ground water in the IPS implementation at the WLA site. The following observations and conclusions are made:

1- Water pumped from both the river and ground water contain silts. The silt content in the ground water is significantly less than that of the river water.

2- Both river and ground water are contaminated, having significant amount of various ions, which are responsible for the high readings of electric conductivity.

3- Visual observation demonstrated that the ground water even though contaminated when used to prepare sodium percarbonate solution was still able to generate gas bubbles.

4- The electric conductivity readings in the WLA silty sand even with the contaminant ions, was smaller than that of Ottawa sand and clean water. This was attributed to the higher tortuosity of the well graded WLA silty sand.

5- The rate of the chemical reaction and gas generation in the WLA silty sand and ground water was faster than in the Ottawa sand and clean water. This implies that there is less time available to prepare and inject the solution as well as shorter wait time before the gas bubble generation is complete.

6- For a given concentration of the chemical solution, the final degree of saturation in the WLA silty sand and ground water is larger than in Ottawa sand and clean water.

7- Flow of the chemical solution through WLA silty sand and ground water is slow. Under vertical gradient of almost 2, the solution took 90 minutes to travel 10.6cm.

8- Installation of the Milwaukee conductivity probe that has two protruding electrodes by pushing into the silty sand layer, is not recommended.
Despite the unfavorable effects of using the WLA ground water in the application of IPS at the WLA site, it was decided, that its use was still a more practical option than trucking vast amount of clean water and using it for solution preparation and injection. It was decide that for all IPS applications, the WLA ground water would be used. For cleaning of storage barrels, hoses, and equipment, the Alamo River water was deemed adequate for use.

6.4 Pilot Field IPS Test

The field IPS test was planned to involve treating a 2mx2m plan area of the silty sand layer present at the WLA site and then shaking it from the ground surface using the T-Rex truck of the NEES@UT Austin. To avoid multiple repetition of the test and to optimize the design parameters of the IPS injection such as the spacing of the injection tubes, and injection pressure and duration, a pilot test was conducted about 20 feet from the designated location of the final IPS test. In this pilot test, conductivity probes played a crucial role in monitoring the test and recording the outcomes in terms of zone of treatment and degree of partial saturation induced by the IPS application.

Figure 6-15 shows the location of the pilot field IPS test relative to the final IPS test location.

Figure 6-15 location of pilot test relative to IPS full production site

This details of the pilot test and the results follow.
6.4.1 Pilot test set-up

Figure 6-16 shows the details of the field set up used for the pilot test.

Two 1.5” diameter PVC closed-ended tubes 40cm apart were driven into the silty sand for extraction and injection, as shown in Figure 6-16. The bottom 18 inches of one of the tubes was perforated all around. This tube was used for extraction of the ground water to enhance the transport of the solution pumped through the injection tube. The injection tube was perforated on only half of the tube surface facing the extraction tube. The tips of both tubes were closed ended and the tubes were driven about 2 feet into the silty sand layer. Prior to the start of injection and extraction, the insides of the two tubes were cleaned by using high pressure water garden hose inserted into the tubes. Figure 6-17 shows a photo of the pilot test set up as seen at the ground surface.
To monitor the injection/extraction process and to determine the zone of influence of the IPS treatment and the degree of partial saturation created, three conductivity probes (CP1, CP2, and CP3) were installed within the silty sand layer and about 10 cm from the injection tube, as shown in Figure 6-16. The details of the installation of the conductivity probes are presented in the next section.

### 6.4.2 Installation of conductivity probes

Earlier tests performed in the field and laboratory clearly demonstrated that conductivity probes would not function properly if pushed into the silty sand layer. A special procedure was successfully devised during the first trip to WLA for the installation of the Milwaukee probes. The procedure entailed the following:

1. Three calibrated probes were tied to each other’s cables at desired spacing (10 inches apart in the pilot test).
2. A 1.5” diameter open-ended PVC tube was driven with a post driver or a sledge hammer, as the need dictated. Occasionally, the inside of the PVC tube was washed with a garden hose to remove the soil plug thus facilitating the driving of the tube. (Refer to Figure 6-18 (a))
3. When the tip of the PVC tube reached the desired depth (depth of the lowest conductivity probe, CP1), the tube was washed, and the string of three CPs with their cables taped together was lowered into the tube. (Refer to Figure 6-18 (b))
While holding the bunched CP cables, slowly the PVC tube was pulled out giving enough time for the sand to cave into the space created and anchoring the CPs one at a time. (Refer to Figure 6-18 (c))

During the process of pull-out of the PVC tube, electric conductivity readings were taken to ensure that the sand around the probes indeed had caved in. Typical values of 1 mS/cm to 1.5 mS/cm confirmed that the CPS were in the WLA silty sand and ground water.

After extracting the PVC tube, bentonite pallets were poured inside the hole left in the clay layer to plug the hole.

Figure 6-18 Procedure for installation of conductivity probes at WLA site

6.4.3 Pilot test results

A chemical solution preparation and delivery system similar to the one used in the laminar box tests was also used at the WLA field site. Details of the IPS implementation at the pilot and final tests at the WLA site are presented in the dissertation of Fritz Nababan. Figure 6-19 shows a photograph of the IPS implementation process. By placing the mixing barrel on top of a wooden crate, a head difference of about 9 feet was achieved to send the solution, thus eliminating the need for an injection pump.
For the pilot test, a 1% sodium percarbonate solution was prepared and injected into the ground. During injection, a negative pressure was applied to the extraction tube to direct the flow towards the conductivity probes. The electric conductivity readings of the three CPs were recorded during injection to detect the transport of solution, and eventually to calculate the degree of saturation. Figure 6-20 presents the recorded data at CP1, CP2, and CP3. The vertical dashed lines on the plots in Figure 6-20 show the time when injection ended.
Initially, all three probes read an electric conductivity of between 1.2 mS/cm and 1.8 mS/cm. These values are consistent with WLA silty sand and ground water. In the laboratory test for a 1% concentration, this initial value was about 1%. In the field, the concentration and the density of the silty sand most likely were not exactly same as those used in the laboratory tests. In any case, the field readings of electric conductivity at the start of the injection were reasonable.

During injection, the electric conductivity of CP1 and CP2 increased to 2.2 mS/cm. This value was close to the peak value measured during bench top test with WLA sand and ground water (1.9 mS/cm). It was concluded that the chemical solution preparation system was able to create a solution with approximate value of 1% concentration. An expected drop in electric conductivity due to bubble generation was not observed at CP1, possibly indicating that the solution arriving at the probe location had very little hydrogen peroxide
left to generate gas bubbles. At CP2, a drop in electric conductivity was observed from point A to point B, as shown in Figure 6-20. The degree of saturation at CP2 was calculated to be 82%, as shown in Equation 6.1.

\[ S = 100 \times \sqrt{\frac{B}{A}} = 100 \times \sqrt{\frac{1.6}{2.2}} = 82\% \quad \text{Eq. 6.1} \]

A small drop before point A at CP2 location is surprising, and can be attributed to possible migration of silts towards the probe location.

The electric conductivity at CP3 location steadily increased to 6 mS/cm, which was higher than electric conductivity of WLA silty sand saturated with 1% solution with ground water (2 mS/cm). This again is surprising and could be attributed to a chemical solution bulb encompassing the probe tip, possibly created by the large amount of gas generated and migrated towards the location of CP3.

In addition to the CP1, CP2, and CP3 readings, the electric conductivity of the outflow from the extraction tube was measured. The purpose was to detect the time of arrival of the chemical solution at the extraction tube location. This would help estimate the radius of zone of partial degree of saturation, under the pilot field test conditions. Figure 6-21 presents the electric conductivity of the outflow from the extraction tube.

![Electric Conductivity of the outflow from the extraction tube](image)

Figure 6-21 Electric conductivity of the outflow from the extraction tube

The initial reading (immediately after the start of injection/extraction process), the electric conductivity reading was 3.4 mS/cm, which is very close to that of the ground water (3 mS/cm) without the chemical solution. Within 30 minutes, the electric
conductivity of the outflow from the extraction tube reached a value of 7.5 mS/cm, and remained steady, with a peak value of 7.9 mS/cm. This value of electric conductivity is smaller than that of the chemical solution with 1% concentration that was sent through the injection tube (~12.5 mS/cm). This can be explained by the fact that while the injection tube aimed the chemical solution in the direction of the extraction tube, the extraction tube sucked water from all around it, thus diluting the arriving chemical solution with ground water from the backside of the extraction tube.

In summary, conductivity probes were used in the pilot IPS field test to evaluate parameters needed to design and implement the final IPS field test at the WLA site. The conductivity measurements led to the following observations:

1. The field procedure devised for the installation of conductivity probe was successful. The procedure entailed: driving an open-ended PVC tube, cleaning the inside by washing, placing a string of conductivity probes inside the tube, pulling up the PVC tube slowly to allow the sand around the probes to cave in and anchor the probes, and finally plugging the hole left by the removal of the PVC with bentonite pallets.

2. A head difference of 9 feet with extraction was sufficient to inject and transport the chemical solution to at least 10 cm in 15 minutes (location of the conductivity probes).

3. Measurement of electric conductivity of the outflow from an extraction tube can be used to detect the first arrival of the chemical solution.

4. A head difference of 9 feet with extraction was sufficient to inject and transport the chemical solution to at least 40 cm in 30 minutes (location of the extraction tube).

5. Chemical solution of 1% concentration can reduce the degree of saturation to 82%, although at two of the three probes, the degree of saturation could not be computed, because of lack of evidence of presence of gas bubbles.

6. The IPS delivery system developed and implemented in the laminar box tests was successfully used in the pilot test and therefore was extensively utilized during the final IPS test at the WLA site.
7. No changes in electric conductivity was observed after the injection process was stopped, and therefore no significant effect of dilution and Ion movement was detected in the field.

6.5 Summery and conclusions

This research project on IPS included field tests at the NEES@UCSB Wildlife refuge site, referred to as the Wildlife Liquefaction Array, WLA site. In all, three trips were made to complete the field tests. The first two were exploratory; the third trip included a pilot IPS field test and the final IPS test in which the treated site was shaken by T-Rex shaker of NEES@UT. This Chapter presented details of the research activities at WLA site that involved the use of electric conductivity probes. The Chapter demonstrated the crucial role conductivity probes played in monitoring and evaluating the outcome of the IPS process in the field. Summary findings are listed below.

1. The well known site conditions at the WLA site determined by other investigators were confirmed by exploratory borings conducted by the IPS research team. Electric conductivity readings also provided confirmation of the depths of the various layers of soil (sand/clay) encountered in the exploratory holes and inside PVC tubes at the IPS test locations.

2. Driving injection tubes was the preferred installation procedure. Jetting a tube into the ground resulted in loose soil around the tube that allowed leakage of injected solution. Conductivity probes confirmed the leaked water to be chemical solution.

3. Both Alamo River water and the ground water at WLA are silty and contaminated. The silt content was less in the ground water than in the River water and therefore ground water was pumped and used in the preparation of the chemical solution for IPS treatment.

4. Installation of a conductivity probe into the sand by pushing was not an acceptable procedure. The readings of the probe were not indicative of the true chemical and electric conductivity conditions in the silty sand at the location of the probe.
5. WLA silty sand treated with chemical solution prepared with the ground water containing contaminant ions exhibited slightly faster rate of reaction than that observed in Ottawa sand and chemical solution prepared with regular tap water. In addition, for the same concentration of chemical solution, the partial degree of saturation in WLA specimen was slightly larger than in the Ottawa sand specimen. Despite these slightly unfavorable conditions resulting from the use of WLA ground water, it was decided to use the ground water for field IPS treatment instead of trucking clean water to the site, which would have been costly and impractical.
Chapter 7

Preliminary Laboratory Tests Using a Prototype Field Electric Conductivity Probe to Estimate Degree of Saturation

7.1 Overview

Chapter 6 described the application of electric conductivity probes in the field tests conducted at the Wildlife Liquefaction Array (WLA). For this purpose, Milwaukee probes, which are typically for use in laboratory tests, were implemented. The installation of the Milwaukee probes in the field was challenging and often resulted in questionable functionality and test results. To install Milwaukee probes, initially a PVC tube had to be driven and cleaned the inside. Then a maximum of three probes (because of limited space available in the tube) with their cables bundled were lowered and the tube carefully lifted to ensure that the probes remained within the soil deposit. There were a number of difficulties and undesirable situation encountered in the field installation of the probes. The driving of a 1.5” diameter PVC tube was very difficult. Washing the inside of the tube to remove the soil plug at times washed also the sand encountered at the tip of the tube, thus loosening the natural sand deposit into which the probes were placed. There was no assurance that the sand caved in around the probes and that there were no pockets of just ground water at the tip of the probes. The bundled three probes limited the recording of data at only three depths.

It was evident that the Milwaukee probes would not be suitable or convenient to use in field application of Induced Partial Saturation (IPS). An alternate field probe was explored, which entailed driving a hollow metal tube with a cone at its tip. The tube would have near its cone tip two electrodes embedded on the surface of the tube, with their cables extended from the inside of the tube to a hand-held meter.
A conductivity probe with electrodes embedded on the surface of a coned tube exists for use in soils of maximum about 1-m thick. FieldScout manufactures such a probe referred to “Direct Soil EC Meter”. In this research, this probe was incorporated in a prototype field conductivity probe that was manufactured for use in field applications of IPS. Laboratory tests were conducted to demonstrate the ability of such probe to provide reliable estimates of electric conductivity and hence degree of saturation with depth of soil.

This chapter describes the details of the prototype field conductivity probe, and presents preliminary laboratory test results.

### 7.2 Prototype field electric conductivity probe

Figure 7-1 shows a photograph of the FieldScout electric conductivity probe. The probe is made of stainless steel tube and is designed to be inserted directly into shallow soil layer (top 1 m) for agricultural purposes. Prior to its use, the probe needs to be calibrated using the calibration solution provided by the manufacturer.

![Figure 7-1 FieldScout electric conductivity meter and probe](image)

Table 7-1 presents the technical specifications of the FieldScout probe, which is extracted from Turf-Tec website ([http://www.turf-tec.com/Instructions/EC1-M-Instructions.pdf](http://www.turf-tec.com/Instructions/EC1-M-Instructions.pdf)).
Table 7-1 Technical specification of FieldScout electric conductivity meter and probe

<table>
<thead>
<tr>
<th>FieldScout Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>0.00-19.99 mS/cm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 mS/cm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>±2% Full Scale</td>
</tr>
<tr>
<td>Calibration</td>
<td>1-point with 2.76mS/cm standard</td>
</tr>
<tr>
<td>Power</td>
<td>Four LR44 1.5V alkaline batteries</td>
</tr>
</tbody>
</table>

7.2.1 Comparison of electric conductivities measured by Milwaukee and FieldScout probes

The FieldScout probe comes in 1 meter long cable and similar to Milwaukee probe the cable had to be extended to 15 feet for use in the field. To ensure that the readings of the FieldScout probe (with the extended cable) are reliable, a comparison of electric conductivities measured by both probes in bench-top tests was made. The bench top-test was very similar to that described in Chapter 3. The sodium percarbonate solution used had a concentration of 1.1%. Figure 7-2 shows the set-up of the bench-top test.

Figure 7-3 presents the test results, which indicate that both probes with extended cables read reasonably comparable electric conductivity values. The slight differences in the readings are within the variability present in the test specimen with respect to density of the sand, potential escape of gas bubbles from a small specimen, and differences in the mechanism and electronics of the two probes.
Design details of prototype field electric conductivity probe

The concept of using a conductivity probe that has its electrodes embedded on the sides of a rod or a tube is very appealing for field applications. In this phase of the research, it was decided to design and manufacture a prototype field electric conductivity probe that will have the promise for easy and rapid implementation during field IPS process. The idea is to push the probe in a deposit of treated or natural deposit of sand and read electric conductivity with depth. The data can then be used to calculate degree of saturation with depth at the location of the test.

To achieve the above stated goal, 1-inch hollow steel rods were purchased in 3-ft segments allowing the extension of the rod to a desired length for penetration into the ground. A truncated aluminum cone was machined, through which the FieldScout probe was inserted with the tip of the probe becoming the tip of the aluminum cone, as shown in Figure 7-4. The FieldScout cone was then fixed to the truncated aluminum cone tip with set screws. The truncated aluminum cone with the probe at its tip was in turn fixed into the hollow steel rod, also with set screws, (refer to Figure 7-4).
Figure 7-4 Prototype field conductivity probe with the FieldScout probe at its tip

The prototype field probe can be pushed into the ground with a special drive coupler attached at its top. The drive coupler allows the cables to protrude from the side leaving the top of the coupler free for pushing or driving. Figure 7-5 shows a photograph of the drive coupler.

Figure 7-5 Drive coupler (a) with a slot to pass probe cable, and (b) rod extension for driving

The prototype field conductivity probe can be assembled in the field prior to the installation. The assembled parts would include the first 3-ft rod segment that has the FieldScout probe. The cables would be pulled through as many 3-ft segments and connecting couplers as needed. Initially, one or two rod segments would be assembled and the drive coupler connected to the top of the last rod segment. After pushing or driving the
probe a few feet into the ground, the drive coupler would be removed, and the next rod already t read would be added to the rod assembly. The drive coupler would then be attached again to the top of the rod assembly and the probe would be pushed or driven again. The process would be repeated until the maximum desired depth is reached. The probe readings can be taken during the installation as well as during pulling out of the probe.

7.3 **Laboratory tests to evaluate the performance of the prototype field electric conductivity probe**

The concept of the field probe is to use it as a means of determining the final degree of saturation at the end of IPS implementation and gas generation. A single probe can then be used by pushing it at various locations and use the information to spatially map degree of saturation at a treated site. This can help to identify need to further IPS treatment at locations that the probe indicates incomplete treatment.

To determine the degree of saturation using Archie’s law described in Chapter 2, two values of electric conductivity are needed, namely the maximum value when the peak concentration of the solution is achieved at the tip a probe, and the final value when the chemical reaction is complete and all the gas is generated. These values of electric conductivity will reflect the effects of the concentration of the chemical solution, void ratio of the sand, and of gas bubble escape, if any. Therefore, the degree of saturation computed by the ratio of these two electric conductivity values will also include all these field in-situ effects.

The question arises as to how the peak value of electric conductivity can be measured in the field, when that value is reached very soon after the injection starts. The plan is to first push the field conductivity probe into the ground at close proximity of an injection tube and to the same depth of the injection tip. Then monitor the probe reading as injection starts. When the solution arriving at the field conductivity probe location is at its maximum concentration, the probe reading will be the peak electric conductivity. When the injection tube is lifted to a different depth, the probe can then also be lifted to the same depth and the reading process repeated. This procedure will provide the peak values of electric conductivity.
conductivity with depth for the sand encountered in the field and for the concentration of the chemical solution used.

The concept of using peak and final values of electric conductivity to estimate degree of saturation was tested in laboratory. The prototype field electric conductivity probe and the planned field implementation procedure were adopted in the laboratory experiment. The details of the experimental set-up are provided in Figure 7-6. The experiment consisted of the following general steps:

Step 1: In an 18-inch barrel, five (5) conductivity probes were placed at about 4 inches from the wall of the barrel and with about 5.1 in (13 cm) vertical spacing (Figure 7-6).

Step 2: A chemical solution with 1 % concentration was prepared in the barrel.

Step 3: Ottawa sand was rained in the barrel, preparing a specimen of 32.2 inch in height. The resulting specimen had a void ratio of 0.7.

Step 4: Immediately after preparation of the sand specimen, the prototype field probe was pushed into the sand (about 4 inches from the barrel wall on the opposite side of the Milwaukee probes), taking reading at each of the five Milwaukee probe elevations. These constituted the peak values of the electric conductivity needed in the calculations of the degree of saturation.

Step 5: The Milwaukee probe readings were recorded periodically until there were no changes in the readings, indicating the completion of the chemical reaction and gas generation.

Step 6: The prototype probe was then pushed back into the sand and readings of electric conductivity were taken at the elevations of the Milwaukee probes.

Step 7: Step 6 was repeated to obtain two sets of readings to ensure the quality of the data.
Figure 7-6 Locations of electric conductivity probes used in the laboratory experiment

Figure 7-7 presents the electric conductivity and calculated degree of saturation results obtained using the Milwaukee probes.

The maximum electric conductivity values ranged between 3 mS/cm and 3.4 mS/cm. This is consistent with the peak values obtained from the bench-top tests for a chemical concentration of 1% (between 2.5 mS/cm and 3.3 mS/cm), as was presented in Chapter 3. The final degree of saturation calculated based on the measured electric conductivity data
was about 64%, which compares well with the calculated degree of saturation in the bench-top tests (60%), for 1% concentration of solution.

Table 7-2 summarizes the peak and final electric conductivity data obtained from the Milwaukee probes and the prototype field probe when pushed in two trials.

Table 7-2 Electric conductivity data from the laboratory tests

<table>
<thead>
<tr>
<th>Probe Location</th>
<th>Milwaukee Peak Electric Conductivity, mS/cm</th>
<th>Prototype Field Peak Electric Conductivity, mS/cm</th>
<th>Final Electric Conductivity, mS/cm</th>
<th>Prototype Field (Trial 1)</th>
<th>Prototype Field (Trial 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>3</td>
<td>3.15</td>
<td>1.4</td>
<td>1.55</td>
<td>1.32</td>
</tr>
<tr>
<td>P2</td>
<td>3.1</td>
<td>3.21</td>
<td>1.4</td>
<td>1.43</td>
<td>1.42</td>
</tr>
<tr>
<td>P3</td>
<td>3.2</td>
<td>3.36</td>
<td>1.4</td>
<td>1.15</td>
<td>1.41</td>
</tr>
<tr>
<td>P4</td>
<td>3.4</td>
<td>3.47</td>
<td>1.2</td>
<td>1.44</td>
<td>1.29</td>
</tr>
<tr>
<td>P5</td>
<td>3.3</td>
<td>3.3</td>
<td>1.2</td>
<td>1.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

The electric conductivity data obtained by the prototype field probe are very comparable with the readings of the Milwaukee conductivity probes. Using the electric conductivity data, degrees of saturation were computed as predicted by the Milwaukee probe and the prototype field probe, in two trials. Table 7-3 presents the results.

Table 7-3 Comparison of degree of saturation obtained by the Milwaukee and prototype field probes

<table>
<thead>
<tr>
<th>Probe Location</th>
<th>Degree of Saturation, %</th>
<th>Prototype Field (Trial 1)</th>
<th>Prototype Field (Trial 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>68</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td>P2</td>
<td>67</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>P3</td>
<td>66</td>
<td>59</td>
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</tr>
<tr>
<td>P4</td>
<td>59</td>
<td>64</td>
<td>61</td>
</tr>
<tr>
<td>P5</td>
<td>60</td>
<td>70</td>
<td>65</td>
</tr>
</tbody>
</table>

A graphic presentation of the comparison of degree of saturation is presented in Figure 7-8. The data fall close to the 45 degree line indicating a good agreement. The slight differences in the degree of saturation from the two probes can be attributed to the variability in the soil specimen at the probe locations, and in the differences inherent in the two probes, which was detected in the tests reported in Section 7.2.1 (Figure 7-3). It is evident that the prototype field probe is capable to make reliable predictions of the degree of saturation in sands under field conditions. In a field application, the probe needs to be inserted adjacent to one of the injection tubes to obtain the peak value of the electric conductivity corresponding to the field conditions including the concentration of the chemical solution being injected. After that, the probe can be inserted at all desired
locations to monitor and map the outcome of the IPS treatment process in terms of partial degree of saturation achieved.

![Figure 7-8 Comparison of degree of saturation obtained by the Milwaukee and prototype field probes.]

### 7.4 Summery and conclusion

Field experience at the WLA site in California using the Milwaukee electric conductivity probe led to the conclusion that this probe is not well suited for use in the field. A prototype field electric conductivity probe was designed and manufactured, which is capable to provide reliable estimates of in-situ values of degree of saturation during and after IPS treatment of sands.

The prototype field electric conductivity probe consists of a hollow steel rod with a cone at its tip that has a commercially available electric conductivity probe (Direct Soil EC Meter, manufactured by FieldScout). This pencil shaped probe has its electrodes embedded on the surface of the tip of the probe. A especial drive coupler was also manufactured that permits the probe cable to protrude from the top of steel hollow tube sideways, out of the way of a hammer that would drive or push the steel rod with the probe at its tip.
This prototype field electric conductivity probe was tested in a laboratory setting following the procedure planned for field implementation. Tests were conducted in which the electric conductivity values were obtained by both Milwaukee and the prototype field probes. The results of the two probes were very comparable and consistent with the electric conductivity values measured in laboratory bench-top tests using a chemical solution of 1% concentration.

Degrees of saturation were computed using the electric conductivity data from both the Milwaukee and the prototype field probes. The results from the two probes were very comparable, with an average difference of about 6%.

Based on the laboratory test results, it can be concluded that the prototype field electric conductivity probe is capable of providing reliable estimates of degree of saturation with depth of soil. Field tests will require to confirm the robustness and ease of use of this probe.
Chapter 8
Summary and Conclusions

This dissertation describes a system developed for monitoring the implementation of an innovative liquefaction mitigation measure referred to as Induced Partial Saturation (IPS). IPS involves injection of sodium percarbonate solution into a potentially liquefiable sand, and through transport of the solution and its reactivity generate gas bubbles within the void spaces of the sand, thus reducing the degree of saturation of the otherwise fully saturated sand. IPS was proposed by Yegian et al., 2007 and through preliminary laboratory tests its beneficial effect on liquefaction resistance was demonstrated.

This research was part of a larger project on evaluating the effectiveness of IPS as a liquefaction mitigation measure. The project was funded by the National Science Foundation (NSF) through the Program George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). Professors M. K. Yegian and A. Alshawabkeh, the PI and CO PI of the project collaborated with Professor S. Thevanayagam, of the State University of New York at Buffalo, Professor Kenneth H. Stokoe of the University of Texas at Austin, Dr. Jamison Steidl of the University of California at Santa Barbara, and Professor Leslie Youd, formerly of Brigham Young University.

To ensure the effectiveness of and the proper implementation of IPS, a monitoring system was designed that utilizes electric conductivity probes. The probes were used to control the concentration of the chemical solution being injected, to monitor the transport of the solution away from the injection point, to detect the rate of generation of gas bubbles and its effect on degree of partial saturation of the sand, to detect potential loss of gas bubbles and its effect on degree of partial saturation, and to estimate the zone of partial saturation created.

The monitoring system developed and the method of calculating the degree of saturation were tested in small- and large-scale laboratory experiments, and in a pilot field test.

Small-scale (bench-top) laboratory experiments were conducted on specimens of Ottawa sand treated by sodium percarbonate. Milwaukee electric conductivity probes were
used to: 1) investigate the rate of gas generation by sodium percarbonate solution within the pores of Ottawa sand, 2) verify the method developed for the calculation of degree of saturation based on readings of electric conductivity of the IPS treated sand, and 3) evaluate the effect of void ratio of the sand on the resulting degree of saturation of the IPS treated sand. The following observations and conclusions were made:

- The reaction of sodium percarbonate with water resulted in generation of oxygen gas. For a given concentration of the chemical solution, the rate of gas generation and therefore reduction in degree of saturation was modeled using an exponential time function.
- The rate of reduction in the degree of saturation, because of gas generation depended on the concentration of the chemical solution. The higher the concentration, the faster was the rate of gas generation and reduction in degree of saturation.
- In a loose specimen of Ottawa sand, chemical solution with concentration ranging from 0.5% to 1.5% yielded partial degree of saturation ranging from 70% to 40%, respectively.
- The procedure developed for the calculation of partial degree of saturation using electric conductivity data was verified by comparing the computed degrees of saturation with values estimated based on volume calculations.
- Tests on sand specimens prepared with different void ratios and treated with chemical solution with concentration of 1% led to the conclusion that void ratio had inappreciable effect on the rate of reduction in degree of saturation and on the final degree of partial saturation.

To explore capability of electric conductivity probes to monitor implementation of IPS in two-dimensions and to determine zone of partial saturated created by IPS, probes were included in two identically prepared laboratory sand specimens in a especially constructed large glass tank (60cm x 91cm x 13.5cm). The experiments had dual purpose of evaluating the benefits of using electric conductivity in IPS implementation, and to validate a computer program developed to simulate IPS process in sands. The glass tank specimens were treated by injecting sodium percarbonate through an injection tube, and reading
electric conductivities and pore water pressures at various locations within the specimens. From these tests, the following observations and conclusions were made:

- Conductivity probes were useful in monitoring the IPS injection process, and detected the arrival of the chemical at the probe locations.
- Electric conductivity readings helped define the zone of partial saturation created. This was confirmed by visual observations made from the sides of the glass tank, as well as by the results of the computer simulations of the IPS process.
- The degree of partial saturation and its spatial distribution determined by the electric conductivity measurements, matched well with the results from the computer simulations and from the bench-top tests corresponding to the concentration of the chemical solution used in the glass tank experiments.

To evaluate the effectiveness of IPS as a liquefaction mitigation measure, laboratory experiments were performed on Ottawa sand specimens prepared in the large (5m x 2.75m x 6m) laminar box of the NEES@Buffalo experimental facility. The experiment was conducted twice. In both tests, the sand was treated by the IPS process and then shaken by a shaker table. Electric conductivity probes were extensively utilized to: 1) control the concentration of the injected chemical solution, 2) determine the desired duration of injection at each location and at various depths, 3) detect the arrival of the chemical at the probe locations distributed within a specimen, 4) record gas bubble escape from within a specimen during and immediately after IPS treatment, 5) compute the partial degree of saturation created and its spatial distribution within a specimen, thus defining the quality and extent of the IPS treatment, and 6) detect any loss of gas bubbles from a specimen due to the shaking of the specimen. The following general observations and conclusions are made:

- Electric conductivity readings taken during injection of the chemical solution were invaluable in monitoring the concentration of the solution, the transport of the solution away from the injection tube, and the injection duration.
- The conductivity probe readings were also helpful in determining the spacing of the injection locations to ensure complete treatment of a sand specimen.
- The probes were able to detect gas bubble escape, and such data were confirmed by visual observations at the surface of a specimen.
• For 1% concentration of the injected chemical solution, the degrees of partial saturations recorded by the probes agreed well with the values observed in the bench-top and glass tank experiments. This confirmed that for loose Ottawa sand there is a unique relationship between partial degree of saturation and concentration of the chemical solution, regardless of the size of the specimen or how the specimen is IPS treated.

• The partial saturation condition of the sand specimen defined by the conductivity probe data was confirmed by the fact that when the specimen was shaken, it did not liquefy. It is noted that a fully saturated sand specimen identically prepared and shaken, liquefied.

• Changes in the conductivity probe readings after the specimen was shaken were inappreciable, indicating that the shaking did not cause loss of gas bubbles.

The scope of the IPS research project included a field experiment at the Wildlife Liquefaction Array (WLA) of NEES@UCSB, in Brawley, California. The purpose of the field test was to evaluate effectiveness of IPS under field conditions. A small region of the potentially liquefiable silty sand layer was treated and then shaken by the large vibratory truck, T-Rex of NEES@UT. Conductivity probes were used in a pilot test in the field to determine: 1) quality of the underground water to be used for the preparation of the sodium percarbonate solution, 2) optimum spacing of injection and extraction tubes, and 3) effect of injecting chemical solution with 1% concentration on reducing the degree of saturation under the real site conditions. The following observations and conclusions were made from the field pilot test using conductivity probes:

• The ground water was very heavily contaminated with variety of ions, which made the initial readings of electric conductivity of the underground sand high. This reduced the capability of the probes to read accurately changes in electric conductivity due to the injection of the chemical solution.

• The rate of the chemical reaction in the sand and contaminated ground water was faster than in sand and clean water. This reduced the overall efficiency of preparing the chemical solution, injecting it, and transporting within the underground sand. The time for the system operation was short and the zone of influence was reduced because of rapid gas generation around the injection tube.
• Injecting and extracting chemical solution with 1% concentration using 9 feet of hydraulic head difference resulted in a treated zone of about 40 cm in radius around the injection tube.

• The final degree of partial saturation achieved in the field was about 82% for chemical solution with 1% concentration.

• The installation of Milwaukee electric conductivity probes in the field by driving a PVC tube, cleaning the inside of the tube, inserting the probe in its bottom, and then slowly extracting the PVC tube to allow the sand to cave around the probe and anchor it, was very difficult and did not always yield reliable results. An alternate field conductivity probe needs to be developed to benefit from all what conductivity probes can provide in the implementation of IPS in the field.

Preliminary work on an alternate field conductivity probe was completed in the laboratory. A pen-shaped electric conductivity probe manufactured by FieldScout for application in shallow soils for agricultural purposes, was inserted at the tip of a segment of a hallow steel tube to create a prototype field conductivity probe. The idea is that this cone-shaped electric conductivity probe can be pushed into the ground and extended by adding more segments to reach a desired depth. The prototype field probe was tested in the laboratory in a sand specimen of about 18 inches in diameter and 32 inches in height, which had Milwaukee conductivity probes placed at desired depths. The specimen was IPS treated and readings of the Milwaukee and prototype field probe were taken and compared. The results led to the preliminary conclusion that the prototype field probe holds great promise for easy use in the field.

In summary, the research reported in this dissertation, demonstrated that electric conductive can be used to monitor large-scale implementation of Induced Partial Saturation (IPS) for liquefaction mitigation. Conductivity probes can provide: 1) quality of the ground water in the field and its impact on the IPS process, 2) rate of chemical reaction leading to gas generation and reduction in degree of saturation, 3) concentration of the chemical solution prepared and injected, 4) information valuable in the design of optimum spacing of injection locations, 5) real-time monitoring of injection duration by detecting arrival of chemical solution and its concentration, 6) zone of treated sand by IPS process, 7) degree of partial saturation achieved and its spatial distribution, 8) potential gas bubble escape
from sand pores during injection or after shaking of a treated sand, and the resulting increase in degree of saturation.
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