AN EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION OF ELECTRICAL RESISTIVITY IMAGING FOR PREDICTION AHEAD OF TUNNEL BORING MACHINES

by

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ABSTRACT

Tunnel boring machines (TBMs) are routinely used for the excavation of tunnels across a range of ground conditions, from hard rock to soft ground. In complex ground conditions and in urban environments, the TBM susceptible to damage due to uncertainty of what lies ahead of the tunnel face. The research presented here explores the application of electrical resistivity theory for use in the TBM tunneling environment to detect changing conditions ahead of the machine. Electrical resistivity offers a real-time and continuous imaging solution to increase the resolution of information along the tunnel alignment and may even unveil previously unknown geologic or man-made features ahead of the TBM. The studies presented herein, break down the tunneling environment and the electrical system to understand how its fundamental parameters can be isolated and tested, identifying how they influence the ability to predict changes ahead of the tunnel face.

A proof-of-concept, scaled experimental model was constructed in order assess the ability of the model to predict a metal pipe (or rod) ahead of face as the TBM excavates through a saturated sand. The model shows that a prediction of up to three tunnel diameters could be achieved, but the unique presence of the pipe (or rod) could not be concluded with certainty. Full scale finite element models were developed in order evaluate the various influences on the ability to detect changing conditions ahead of the face. Results show that TBM/tunnel geometry, TBM type, and electrode geometry can drastically influence prediction ahead of the face by tens of meters. In certain conditions (i.e., small TBM diameter, low cover depth, large material contrasts), changes can be detected over 100 meters in front of the TBM. Various electrode arrays were considered and show that in order to better detect more finite differences (e.g., boulder, lens, pipe), the use of individual cutting tools as electrodes is highly advantageous to increase spatial resolution and current density close to the cutterhead.
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LIST OF SYMBOLS

\( \rho_a \) Apparent electrical resistivity

\( f_1 \) Frequency 1

\( f_2 \) Frequency 2

\( V \) Electrical voltage (electrical potential difference)

\( K \) Geometric factor

\( I \) Electrical current amplitude

\( \rho \) Electrical resistivity

\( \sigma \) Electrical conductivity

\( s \) Side length

\( j \) Electrical current density

\( E \) Electric field

\( \nabla \) Gradient

\( \mathfrak{I} \) Electrical current point source/sink

\( \varphi \) Porosity

\( \phi \) Volume fraction of pore space filled with water

\( \sigma_w \) Electrical conductivity of water

\( \alpha \) Tortuosity factor

\( m \) Cementation exponent

\( n \) Saturation exponent

\( \sigma^* \) Complex conductivity

\( \sigma' \) Real component of complex conductivity

\( \sigma'' \) Imaginary component of complex conductivity

\( m_a \) Chargeability

\( V_p \) Primary voltage
\( V_s \) Secondary voltage
\( t \) Time
\( f \) Frequency
\( \Phi \) Phase
\( Z \) Electrical impedance
\( i \) Imaginary number
\( \omega \) Frequency
\( \sigma_{AC} \) Magnitude of electrical conductivity for injected AC current
\( \sigma_{DC} \) Magnitude of electrical conductivity for injected DC current
\( f_{AC} \) Frequency of injected AC current
\( f_{DC} \) Frequency of injected DC current
\( r \) Radial distance
\( \sigma_a \) Apparent conductivity
\( \Psi \) Electrical potential
\( a \) Wenner electrode array spacing
\( V_{MN} \) Voltage between electrodes M and N
\( z_{PLANE} \) Depth of planar difference
\( z_{max} \) Maximum distance in z-direction of current density propagation
\( V_{FAR-FIELD} \) Far field voltage; equilibrium condition
\( H_{TANK} \) Height of experimental tank
\( H_{TBM} \) Location of front of TBM cutterhead from bottom of experimental tank
\( R_{TANK} \) Radius of experimental tank
\( S_e \) Degree of saturation
\( D_{electrode} \) Diameter of electrode
\( D_{TBM} \) Diameter of experimental model TBM
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_D$</td>
<td>Separation distance (z-direction) between front of TBM cutterhead and metal pipe/rod</td>
</tr>
<tr>
<td>$\sigma_L$</td>
<td>Electrical conductivity of the tunnel lining</td>
</tr>
<tr>
<td>$\sigma_{TBM}$</td>
<td>Electrical conductivity of the TBM</td>
</tr>
<tr>
<td>$\sigma_{AIR}$</td>
<td>Electrical conductivity of AIR</td>
</tr>
<tr>
<td>$\sigma_G$</td>
<td>Electrical conductivity of grout</td>
</tr>
<tr>
<td>$\sigma_A$</td>
<td>Electrical conductivity of the annulus</td>
</tr>
<tr>
<td>$\sigma_D$</td>
<td>Electrical conductivity of the disk</td>
</tr>
<tr>
<td>$\sigma_{CT}$</td>
<td>Electrical conductivity of the cutting tool</td>
</tr>
<tr>
<td>$t_A$</td>
<td>Thickness of the annulus</td>
</tr>
<tr>
<td>$t_D$</td>
<td>Thickness of the disk</td>
</tr>
<tr>
<td>$C$</td>
<td>Tunnel cover depth</td>
</tr>
<tr>
<td>$s$</td>
<td>Current source/sink separation distance</td>
</tr>
<tr>
<td>$x_{\text{max}}$</td>
<td>Maximum distance in x-direction of current density propagation</td>
</tr>
<tr>
<td>$x_D$</td>
<td>Separation distance (x-direction) between front of TBM cutterhead and change ahead of TBM</td>
</tr>
<tr>
<td>$x_L$</td>
<td>Look-ahead distance</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle from horizontal (x-y plane) of the angled difference</td>
</tr>
<tr>
<td>$\sigma_{\text{PIPE}}$</td>
<td>Electrical conductivity of metal pipe</td>
</tr>
<tr>
<td>$d_{\text{PIPE}}$</td>
<td>Diameter of metal pipe</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>$F$</td>
<td>Force total</td>
</tr>
<tr>
<td>$F_{\text{tools}}$</td>
<td>Force on individual cutting tool</td>
</tr>
<tr>
<td>$R_{\text{earth}}$</td>
<td>Electrical resistance of the earth</td>
</tr>
<tr>
<td>$R_{\text{TBM}}$</td>
<td>Electrical resistance of the TBM</td>
</tr>
<tr>
<td>$R_{\text{human}}$</td>
<td>Electrical resistance of a human</td>
</tr>
</tbody>
</table>
$i_s$  Electrical current source amplitude for entire circuit

$i_1$  Electrical current amplitude through circuit leg 1

$i_2$  Electrical current amplitude through circuit leg 2

$i_3$  Electrical current amplitude through circuit leg 3
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To my wife and best friend: The last four years have been at times the best and the worst of my life. You have seen me through the good and the bad and our bond is even stronger than ever. Thank you for your support and encouragement through everything. I love you with all my heart and I cannot wait to explore the furthest spans of the world with you. I hope I can find a way to repay for all that you've given to me.
CHAPTER 1
INTRODUCTION

1.1 Introduction and Motivation

This dissertation presents the experimental and computational studies that investigate the application of electrical resistivity theory to the prediction ahead of the tunnel face during tunnel boring machine (TBM) excavations. Electrical resistivity offers a real-time and continuous imaging solution to increase the resolution of information along the tunnel alignment and may even unveil previously unknown geologic or man-made features. The experimental and computational studies presented herein break down the tunneling environment and the electrical system to understand how their fundamental parameters can be isolated and tested, identifying how they individually influence the ability to predict changes ahead of the tunnel face. This chapter will summarize the current state-of-the-art in electrical resistivity methods applied to the prediction ahead of the tunnel face and the research motivation. Research questions and a dissertation outline is included.

TBMs have become one of the most popular tools for the excavation of underground tunnels because of their versatility and efficiency. TBMs are designed for use in hard rock (e.g., sandstone, shale) and soft ground (e.g., sand, silt, clay), and are manufactured for a large range in tunnel diameters from micro-TBMs (0.6m to 2m) to larger transit sized tunnels (2m to 16m). Due to the increasing demand of above ground space in densely populated cities, the tunneling industry has seen a large demand of underground tunnels for transit, utilities and water transport. Projects with highly complex geology present a high degree of uncertainty as current site investigation practices are only capable of characterizing, with certainty, a relative point of information in three-dimensional space. Potential consequences of excavation through unidentified changes are damage to the machine, surface settlements (particularly dangerous for excavations below densely populated cities) and even fatalities. By itself, machine damage
can result in millions of dollars in unnecessary costs. Therefore, methods which can help to increase the certainty of the remaining ground characterization are of great importance as they may be useful for improving ground truth, and therefore, reducing the risk involved in the excavation process.

A number of geophysical methods have been explored for the use in the tunneling environment for prediction ahead of the face. While this dissertation focuses specifically on electrical resistivity, acoustic/seismic methods have been well-established for use in the tunneling environment, particularly in hard rock. In the last decade, a few commercially available products have been used on projects and some research has been carried out, which evaluates electrical resistivity as a candidate for prediction ahead of the tunnel face. However, details regarding implementation and fundamental studies are extremely limited. A number of aspects are not address such as:

1) the electrical interaction between the formation and various TBM types through what is called ‘the interface region’

2) optimization of electrode configuration

3) evaluation of the tunnel geometry and influence of the metallic TBM

The research presented here explores these kinds of fundamental uncertainties in order to address if electrical resistivity can be a viable means to predict changes ahead of the TBM. This lack of fundamental knowledge for a topic of such great importance to the industry provides a strong motivation for this research.

A recent example of potential consequences of not being able to image ahead of the TBM are the events occurring during The Alaskan Way Viaduct Replacement Program (SR99) in Seattle, Washington. SR99 was initiated to replace the existing viaduct two-tier highway system that spans parallel to Seattle’s coastline. It was deemed that this structure was in danger of failure under earthquake loading. Instead of retrofitting the existing structure or replacing it,
the city of Seattle decided to create a new two mile long, two-tier underground tunnel. The alignment design is shown in Figure 1.1

![Figure 1.1: Designed tunnel alignment for the SR99 tunnel](image)

The TBM design was contracted through manufacturer Hitachi Zosen for a 17.4m diameter earth pressure balance (EPB) TBM. The largest diameter machine of its kind, known as 'Big Bertha', is named after a former mayor of the city named Bertha Knight Landes. A photo of Big Bertha is shown in Figure 1.2.

![Figure 1.2: Image of the SR99 TBM called Big Bertha](image)

SR99 started excavation on July 30th, 2013 at the south portal (shown in Figure 1.1). On December 6th, 2013, after only 330 meters of excavation, the TBM was stopped shortly after
mining through an unknown obstruction, a steel pipe used to monitor groundwater. For the next few months, several studies took place and revealed significant damage to the machine including failure of the main bearing and damage to a number of cutting tools. Early speculation claimed a few reasons for the damage but no reports have been released that conclusively point to a single culprit.

Two years later, Big Bertha finally resumed excavation on December 22nd 2015. In January of 2016, a massive sinkhole (Figure 1.3) opened above the machine and again excavation was ceased. The cause of the sinkhole has not yet been confirmed.

![Image of sinkhole over SR99 excavation](image)

**Figure 1.3: Sinkhole developed over SR99 excavation**

The causes for the damage to the machine and the sinkhole are unclear, however, it is clear that the current practice for the evaluation of what lies ahead of the TBM is not sufficient. Methods that can evaluate the conditions ahead of the TBM have clearly become a necessity in order to avoid these situations.
In the last couple of decades, the application of electrical resistivity to the tunnel environment (TBM and conventional excavations) has been attempted but with few publications pertaining to specific details of implementation or interpretation of results. Furthermore, commercially available systems do not yet seem to be widely accepted as state-of-practice in the tunneling industry. Given the apparent success of electrical resistivity for a number of other applications (e.g., petroleum, hydrogeology, mining) it is unclear why these methods have not yet been abundantly used in the multi-billion dollar industry of tunneling. The following state-of-the-art review will summarize the current theory, practice and limitations of existing knowledge for this topic.

1.2 State of the Art in Electrical Resistivity Applied to TBMs

Two commercially available systems called the Bore-tunneling Electrical Ahead Monitoring (BEAM) system [1] and the BEAM4 [2] were developed over the last two decades to be fully integrated into TBMs for the prediction ahead of the tunnel face. Both systems use electrical resistivity (called DCR) and induced polarization (IP) methods to characterize the material ahead of the face. A detailed review of DCR and IP methods will be given in Chapter 2 and additional information may be found in literature (e.g., [3], [4], [5]).

The BEAM and BEAM4 use the injection of low frequency sinusoidal alternating electrical current to create an electric field (measured as a voltage across two electrodes). The electric field is related to the injected current by the spatial distribution of resistive (or conductive) materials. The resistivity (or conductivity) at any point in space is a function of a number of pore space characteristic such as porosity, permeability, pore fluid temperature (e.g., [6], [7], [8]) and clay content (e.g., [9]). These pore space characteristics can be related to macro-scale lithological characteristics such as grain size distribution, fracture density and even lithology (e.g., [10], [11]).

GeoExploration Technologies’ BEAM system (illustrated in Figure 1.4) is comprised of a three electrode array that is integrated into the TBM and tunnel. Electrical current is injected
through the guard electrode (A1) and the measuring electrode (A0), and the current is retrieved by the sink electrode (B). A separation of the injected current to A1 and A0 aims to ‘focus’ current ahead of the TBM as illustrated in Figure 1.4. The idea of current focusing is widely researched in the petroleum industry in borehole-based implementations with the use of several electrodes to constantly monitor voltages and inject guard currents to focus the measuring current (e.g., [12], [13]). This will be discussed in Chapter 2, specifically applied to borehole-based implementations. The BEAM system describes current focusing through similar voltage monitoring, but between electrodes A0 and A1 in order to continuously set the voltage between them to zero (i.e., zero current flow between the electrodes). Therefore, any current injected through the measuring electrode A0 is focused ahead of the cutterhead instead of flowing back to the shield of the TBM. Given the large metallic composition of a TBM, is it not expected that the cutterhead is electrically isolated from the shield, and so focusing current through a separation of the cutterhead and the shield would require electrical isolation of these two bodies.

Alternating current is typically injected at two different points in time for two separate frequencies, $f_1 = 20\text{Hz}$ and $f_2 = 200\text{Hz}$, over a measurement cycle of 2-10 seconds. Each measurement cycle is averaged with a reported resolution of 1.0 – 1.5m along the alignment of the tunnel [1]. Electrical resistivity can be calculated through Ohm’s law, which describes the relationship between voltage ($V$), current ($I$) and apparent electrical resistivity ($\rho_a$). Equation 1.1 shows how resistivity (denoted with ‘a’ as apparent resistivity) is related to the injected current amplitude and the measured voltage through what is called the geometrical factor, $K$. Chapter 2 will provide a detailed review of electrical resistivity theory.

$$\rho_a = \frac{VK}{I} \quad (1.1)$$
By using the two apparent resistivity measurements from $f_1$ and $f_2$, two difference quantities are reported:

1) The amplitude of apparent electrical resistivity, given by $f_1$, $|\rho_a(f_1)|$ (Ω·m)

2) The percent frequency effect (PFE), which is defined in Equation 1.2:

$$PFE\% = \left( \frac{\rho_a(f_1) - \rho_a(f_2)}{\rho_a(f_2)} \right) \times 100\%$$

($\rho_a(f_i)$ is generally a function of the bulk pore fluid characteristics such as porosity, permeability, temperature, saturation, etc. PFE aims to evaluate the imaginary component of the so-called complex resistivity (or complex conductivity), which describes the ability of the material to hold a charge and is generally a function of clay content. $|\rho_a(f_i)|$ and PFE will be discussed in detail in Chapter 2. An example of recorded measurements, $|\rho_a(f_i)|$ and PFE, along a tunnel alignment is shown in Figure 1.5.

For an individual measurements of $|\rho_a(f_i)|$ and PFE, their values can be calibrated to site specific geologic testing. An example of a matrix developed for the BEAM system for a specific site is given in Figure 1.6. Kaus and Boening [1] discusses a generalized lithological classification system that is dependent upon typical observed values in PFE:
- Clays and silts, PFE >15%
- Sands 15% > PFE > 0%
- Gravels, faults, fractures, karst zones, cavities PFE < 0

**Figure 1.5: BEAM display showing |\(\rho(f_1)|(\Omega\cdot m)\) and PFE(%) [1]**

In general, a relatively larger value of PFE describes a material with one or two characteristics, 1) relatively smaller grain size yielding smaller pore size, 2) relatively higher clay content. With all else equal, these characteristics generate a larger imaginary component of complex resistivity and will be discussed in detail in Chapter 2. Using Equation 1.2, a larger PFE results from an increasing contrast between \(\rho_a(f_2)\) and \(\rho_a(f_1)\). For gravels, faults and karst cavities, a negative PFE can be achieved through the condition \(\rho_a(f_1) > \rho_a(f_2)\).
There are two modes of operation advertised for the BEAM and the BEAM4. The first mode, as described above for current focusing, is called ‘integral mode’ (shown in Figure 1.4) and it uses an electrically isolated cutterhead and shield of the TBM - both for current injection and electrical potential measurement. Due to the relatively large size of the TBM, this mode inherently averages a statistically heterogeneous material as a homogeneous material across the tunnel face.

The second mode is called ‘scan mode’ (shown in Figure 1.7) and uses electrically isolated individual cutting tools to collect data at various radii and sweeping around the tunnel face during the rotation of the cutterhead. In theory, scan mode provides greater spatial resolution of measurements for mapping information at different lateral locations at the tunnel face. Figure 1.8 shows an example of how scan mode can plot PFE as a contour plot across the face of the cutterhead and detect heterogeneities. This contour plot shows the ability to resolve a negative PFE region in the upper left hand corner suggesting an anomaly ahead of the TBM.
The BEAM system has reported a prediction ability of up to three tunnel diameters in hard rock and less in soft ground depending upon the resistivity (or conductivity) of the earth. Using scan mode, BEAM reports a spatial resolution and lateral accuracy of 0.5m and 1m, respectively [14].

Figure 1.7: BEAM system scan mode [1]

Figure 1.9 summarizes the entire collection of projects where the BEAM and BEAM4 systems were used throughout the world between their initial inception and 2016. A much larger number (compared to other countries) of tunnel projects used either the BEAM or BEAM4 in China, Italy and Spain, totaling 14, 10 and 7 projects, respectively (87 total projects). For other countries, projects fall to only a few implementations or less. Currently, no implementations have been performed in the United States and only one implementation in Canada. Figure 1.10 shows an alternative view of these same projects categorized by year, since 2000. It is important to note that there exist no publications for any of the projects summarized in the graphs below.
In the last few years a system called the Tunnel Electrical Resistivity Prospecting System (TEPS) has emerged from Ryu et al. (e.g., [15]). The limited published documentation ([15] and [16]) on TEPS suggests use for both conventional and TBM excavated tunnels but discussion of implementation or results is somewhat limited. An illustration of the implementation for the TEPS is shown in Figure 1.11.

Figure 1.11 shows a generalized setup for the TEPS for conventional tunneling prediction. Electrodes or “sensors” are secured to the tunnel face, each with a separate electrical connection to the resistivity meter or “equipment”. For the field tests presented in Ryu [15] the material of the electrodes is not given, but state a 2cm diameter with no mention of length. The “sensors” are positioned within a predrilled hole in the tunnel face approximately 10-15cm long. The resistivity meter takes measurements and will send data back to the computer for inverse analysis.
In his dissertation, Ryu [15] investigated the application of the TEPS but for a conventional excavation to evaluate either a) the presence of an anomaly ahead of the face, b) potential collapse or c) estimation of rock conditions. A result given by Ryu [15] is shown in
Figure 1.12. According to the dissertation, this study showed that the TEPS could predict larger regions of changing rock conditions and identified “weak zones” through regions of contrasting electrical resistivity four to five tunnel diameters ahead of the tunnel face. A major limitation of this study for the application to TBMs is that it does not take into account for the presence of a highly conductive TBM.

The dissertation makes no mention of measured values of voltage or level of injected current, but state that the resistivity meter is allowed to range voltage and current between 10-20V and 1μA to 1A, respectively. No mention of alternating current is discussed and so it is assumed that no IP measurements are recorded for these studies. The recorded values of resistivity ranged within typical hard rock conditions (500Ωm – 1,000,000Ωm).

Park et al. [17] presents another electrical resistivity system called the TBM Resistivity Prediction (TRP) system for predicting conditions ahead of the face including location, thickness, permittivity ratio and electrical conductivity. Field tests were performed for an EPB TBM where two electrodes are employed through the cutterhead during a cease in excavation (Figure 1.13). In order to determine a change ahead of the machine, the electrode array is first calibrated for different contact points at the tunnel face for a condition that is relatively homogeneous and for a known electrical conductivity. At a location where a change is anticipated, a cease in excavation is given and electrical resistivity measurements are taken at the face. Measurements are compared to the calibrated measurements in order to verify a change ahead of the TBM.

According to the study, the electrode array was capable of predicting an amphibolite transition zone ahead of the machine. Park et al. [17] showed measured resistivity values of 90Ωm and 100Ωm (100 Ωm reference resistivity). In this paper, there is no discussion of recorded voltage amplitudes or levels of current injection.
Cho et al. [16] highlighted the importance of cutting tools as electrodes for TBM tunneling applications in order to scan the earth as the BEAM and BEAM4 systems suggest. Specifically, they investigated the electrical isolation through retrofitting a disc cutter mount and insulating the disc through custom manufactured parts with a material called polyetheretherketon (PEEK). Cho et al. [16] suggests that PEEK held strong results for yield
strength, flexural strength and low electrical properties, but did not specify any values, testing procedures or comparison to other materials.

Figure 1.13: Two electrode array used for electrical resistivity measurements at the tunnel face through the cutterhead (a) connected steel pipes used as electrode is jacked into place, (b) view of electrode through cutterhead spoke and touching the tunnel face [17]

Mooney et al [18] presents a computational finite element study that investigates the use of DCR methods on a 10m diameter TBM in homogeneous ground conditions as it advances toward a vertical planar difference or a vertical planar inclusion. Figure 1.14 shows the computational results for various contrasts of electrical conductivity between the homogeneous ground, $\sigma_1$, and the vertical planar difference, $\sigma_2$. This study showed that the prediction (so called look-ahead distance) ability of electrical resistivity is increased as the conductivity contrast, $\sigma_2/\sigma_1$, is increased. These results show that the electrode configuration can easily detect the planar difference up to five TBM diameters (50m) ahead of the TBM without introduction of electrical noise. When noise is introduced, the look-ahead distance is decreased and the planar difference goes undetected until a signal to noise ratio of greater than one is achieved.

An additional model was given by Mooney et al. [18] to assess the prediction ability for a vertical planar inclusion of width, $b$(m). Figure 1.15, presented in Mooney et al. [18], showed that as the width of the inclusion, $b$, is increased, then the look-ahead distance is also
increased. Compared to the results for a vertical planar difference, a similar decrease in the look-ahead distance is observed when electrical noise is introduced. An important point about the results presented in this study is that the models disregards the imaginary component of complex conductivity and assume only the real part exists. The relationship is shown in Equations 1.3 and 1.4, where $\sigma^*$ is called the complex conductivity, $\sigma'$ is called the real part of complex conductivity, $\sigma''$ is called the imaginary part of complex conductivity and $i$ is the imaginary number. This paper proves that this is a fair assumption as the imaginary component is often relatively zero compared to the real component of complex conductivity.

$$\sigma^* = \sigma' + i\sigma''$$  \hspace{1cm} (1.3)

$$\sigma^* = \sigma' ; \sigma'' = 0$$  \hspace{1cm} (1.4)

![Diagram](image)

**Figure 1.14: Influence of $\sigma_1$, $\sigma_2$ and $d/D$ on the difference in potential and apparent conductivity [18]**

The successful computational study performed by Mooney et al. [18] streamlined the initiative of this research for further investigation of these techniques, particularly related to what
influences the measurements. The study of what influences electrical resistivity applied to the
TBM tunneling environment has two potential benefits:

1) It may shed some light on why these methods have not be widely accepted in the
tunneling industry (i.e., why they may be successful for some projects but not for others)
2) By understanding the variables that influence an electrical resistivity measurement, the
process of inversion becomes more accurate and more unique to what lies ahead of the
TBM.

Figure 1.15: Influence on difference in electrical potential (V) of an anomaly of width,
b(m), at a distance, d(m), ahead of the TBM for electrical conductivities, \( \sigma_2 (\text{S/m}) = 1, 0.1, 0.001 \) [18]

1.3 Other Geophysical Prediction Techniques Applied to TBMs

Other geophysical monitoring techniques have shown promise for prediction ahead of
the TBM including passive seismic and active acoustic methods. Tunnel Seismic While Drilling
(TSWD) developed by Brückl et al. [19] and While Drilling Tunnel Seismic Profile (WDTSP)
developed by Petronio and Poletto [20] are two techniques that passively monitor the vibrations
induced between the interaction of the TBM and the earth during the excavation process. These
methods are advantageous because they can be used continuously used while the TBM excavates (i.e., no down time required for measurement). A significant difficulty in these measurements lies in the interpretation of the passive seismic signal in order to map changes ahead of the machine since the machine vibration is a constantly changing signal.

Active acoustic techniques involve the use of injecting an acoustic emission of known amplitude, frequency and origin from a transducer. The acoustic wave travels through the earth until it reaches an impedance contrast (i.e. material with contrasting wave speed). A part of the wave is reflected and can be measured by a receiver where the signal can be related to the material contrast and its location in front of the TBM. Active methods are advantageous because the acoustic signal is well defined and so reflections can be directly correlated to what lies ahead of the machine. The downside to active methods is that the machine must be stopped for a relatively noise free measurement process.

Within the last several years, Herrenknecht has developed a commercially available active acoustic system called sonic soft ground probing (SSP). The SSP system has reported the ability to predict ahead of the tunnel face up to 40m with a spatial resolution of up 0.5m, depending upon the frequency content and wave speed of the material ahead of the TBM [21]. A known difficulty for both passive seismic and active acoustic methods is that they rely on material with a large modulus (i.e. high wave speed) in order to see reflections further ahead of the face. When the wave speed of the material is too low, attenuation of the wave is a concern and so very small prediction distances are achieved. In general, soft ground materials (e.g., clays, sands) have lower wave speed than hard rock (e.g., shale, granite, limestone).

Research Questions and Objectives

The overarching goal of this research was to determine if electrical resistivity can be successfully applied to a TBM in order to predict changes ahead of the tunnel face for both hard rock and soft ground conditions. Yet, there are several fundamental research questions that are identified that contribute to the broader goal of predicting ahead of the face:
1. What type of measurable data can be used to show a detected difference? How is this information displayed to inform the excavation process?

2. What levels of contrasts in size/material can be detected (i.e. could a relatively small boulder with a conductivity close to that of the surrounding earth be detected?)?

3. Does the TBM tunneling method (open-face, slurry, EPB etc.) influence the ability of electrical resistivity to detect/image geologic or man-made differences ahead of the TBM?

4. Does the electrode array geometry (relative electrode spacing) significant influence the ability to detect/image geologic or man-made differences?

5. Does the tunneling environment geometry (diameter, cover, etc.) influence the ability to predict changes?

Through a combination of experimental and computational studies, the research was directed in order to answer the above research questions. The following describes the order of the dissertation.

In Chapter 2, a detailed background of geophysical electric methods is given to build a strong theoretical background on the methods and well-established applications of geophysical electric measurements. Presented therein is a combination of DCR and IP methods, which aims to fully characterize the so-called complex conductivity of a material. While this dissertation does not specifically study IP methods as they apply to predication ahead of the TBM, a knowledge of their existence identifies a limitation of this research and so encourages future research for the extension to IP methods.

Chapter 3 presents a scaled experimental study which simulates a TBM excavating toward metallic pipe (or rod) of known location. This study was originally developed to mimic the commercial implementation of the BEAM and BEAM4 systems. As the TBM excavates towards the pipe (or rod), electrical resistivity measurements are taken for two difference electrode configurations that aim to represent their commercial counterparts called integral mode and
scan mode. This study aims to evaluate if a simple experimental study is capable of identifying a change ahead of the TBM and if that change can be identified as a pipe (or rod).

In Chapter 4, a full scale computational finite element model is presented to evaluate the influence of TBM type (slurry, earth pressure balance, and hard rock) on the ability to predict a change ahead of the tunnel face by defining and varying the so-called interface region. The interface region describes the physical volume that separates the TBM from the formation around the TBM. The influence of the interface region is evaluated for six unique electrode arrays.

Chapter 5 identifies two of the most promising electrodes arrays from Chapter 4 to evaluate the sensitivity of various changes ahead of the TBM. This research simulates various geologic changes (e.g., seam, diagonal difference, boulder) and a metallic pipe in front of the TBM.

Chapter 6 uses the same two electrode arrays from Chapter 5 in order to understand the geometrical influence of the electrode array and the TBM/tunnel on the ability to predict ahead of the tunnel face. In this chapter, the identified geometric variables are parametrically tested by changing one variable and holding the others constant.

Appendix A provides some field implementation considerations including some discussion on the components of the TBM for use as electrodes, different TBM types and how they operate. The appendix also details the design and fabrication of parts for electrical insulation of a scraper cutting tool.

In Appendix B, a circuit analysis is presented (from Schaeffer [52]) for the safe levels of current injection/retrieval.

The experimental and computational studies presented in this dissertation add to the state of the art for the prediction ahead of the tunnel face using electrical resistivity as current knowledge is either not well documented or does not yet exist, particularly when tunnel excavations are performed by TBMs. By breaking down the TBM tunneling environment into
relevant influences that affect the flow of electrical current and understanding the variables that influence the ability to predict ahead of the tunnel face, this study can a) be informative to optimize field implementations and b) enhance accuracy and uniqueness of geophysical inversions
CHAPTER 2
BACKGROUND ON GEOPHYSICAL ELECTRIC METHODS

2.1 Introduction

Geophysical techniques are commonly used in geological and hydrogeological exploration and have seen increasing popularity for the non-destructive evaluation\(^1\) of geo-materials (e.g., foundations, soil and rock, grout). Each unique geophysical method relies on its governing physics to evaluate the spatial distribution in a governing material property. For example, acoustical methods use wave transmission to detect acoustic impedance contrasts and identify the so-called ‘wave speed’ of the material.

Two geophysical methods, which are based upon the fundamentals of electrical flow, called direct current resistivity (in literature referred to as DCR or resistivity) and induced polarization (IP), assess the behavior of electricity as it flows through geo-materials. These electrical methods were first commercially introduced over a century ago for the application to well logging (e.g., [12], [22]). Due to their relatively flexible installation, DCR and IP methodology can be applied to an extensive range of survey sizes from large field-scale (kilometers) to very small laboratory-scaled (centimeters) implementations [10]. DCR and IP are two of the most common geophysical techniques for subsurface investigations because of their versatility and ease of implementation. Since their commercial introduction to well logging and geological formation mapping, these methods have been adapted and applied to many other applications including mining, subsurface site investigation, groundwater flow, contaminant tracing and tunneling (e.g., [23], [24], [25], [26]).

DCR and IP aim to capture an image of the spatial distribution of low-frequency resistive and capacitive nature of geo-materials within a space of interest. While the initial installation of

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\(^1\) The term “evaluation” can be expressed for quality assurance (QA), risk management, and characterization of subsurface investigations.
these two methods may appear similar, the data acquisition and analysis are quite unique from one another. The following sections will fundamentally compare these two techniques and outline a couple of common implementation strategies.

2.2 Direct Current Resistivity (DCR)

DCR uses active direct current (DC\textsuperscript{2}) or very low frequency alternating current (AC) injection and simultaneous measurement of discrete points within an induced electric field to predict the governing material property called the electrical resistivity. Since the subsurface contains many heterogeneities, the objective of DCR is to capture an image of the spatial distribution in electrical resistivity [27].

A material’s electrical resistivity, $\rho$(\Omega\cdot m), quantifies its opposition to the flow of electrical current. A relatively large value in $\rho$ describes a material that strongly resists the flow of electrical current. Literature often uses the term “electrical resistivity” to describe the material property, however, it also uses this term to identify with the method itself. To avoid confusion, this dissertation will refer to the electrical conductivity as the prevailing material property. The numerical value of resistivity and conductivity are simply the reciprocal of one another as shown in Equation 2.1.

$$\sigma = \frac{1}{\rho} \tag{2.1}$$

where, $\sigma$ (S/m), is the electrical conductivity and describes the how easily current can pass through a material.

Figure 2.1 shows a homogeneous block with a side length, $s$. The block will allow an electrical current, $I$, to pass through it to the extent of its defined $\sigma$. As electrical current passes from one side of the block to the other, a potential difference, $V$, is created and can be

---

2 A square wave form for DC injection negates the electrical polarization of a material resulting from prolonged exposure to a constant polarity of DC.
measured as the potential drop from one side of the block to the other. The electrical conductivity of the homogeneous material is given by Ohm’s Law:

\[
\sigma = \frac{I}{s} \frac{1}{VA}
\]  

(2.2)

Figure 2.1: Electrical flow through a homogeneous block

where, \( I \) (Amps), is the magnitude of electrical current, \( s \) (meters), is the length of current propagation, \( A \) (m\(^2\)), is the cross sectional area perpendicular to electric flow, and \( V \) (Volts), is the potential drop (or voltage) that occurs over the length of current propagation.

Geo-materials do not often present themselves as homogeneous with a uniform conductivity such as in Figure 2.1. In many cases complex heterogeneities are present and special consideration must be given for a spatial distribution of Ohm’s law. In order to account for the a varying spatial distribution of electrical conductivity, a three-dimensional spatial Ohms’ Law (Equation 2.2) expresses the relationship between \( \sigma \) (S/m), the macroscopic current density \( j \) (A/m\(^2\)), and the electric field \( E \) (V/m). The electric field can be expressed as the voltage (or potential difference), \( V \) (V), over a known distance as shown in Equation 2.3.
\[ j = \sigma E \]  \hspace{1cm} (2.2)

\[ E = -\nabla \Psi \]  \hspace{1cm} (2.3)

The continuity equations are shown for areas where current is injected (Equation 2.4) and areas not subjected to current injection (Equation 2.5), where \( \mathcal{J} \) is the electrical current source (or negative for a sink) term corresponding to volumetric charge (A/m\(^3\)). The combination of Equations (2.2-2.5) leads to Equation (2.6), which relates \( \Psi \) to the conductivity, \( \sigma \).

\[ \nabla \mathcal{J} = \mathcal{J} \]  \hspace{1cm} (2.4)

\[ \nabla \mathcal{J} = 0 \]  \hspace{1cm} (2.5)

\[ \nabla \ast (\sigma \nabla \Psi) = 0 \]  \hspace{1cm} (2.6)

Out of all material properties, the electrical conductivity of geo-materials presents one of the largest ranges (approximately \( 10^{-16} \) S/m to \( 10^7 \) S/m). Many studies have attempted to provide ranges of electrical conductivity for various earth materials, where most earth materials fall within a range of \( 10^{-4} \) to 5 S/m [10]. Figure 2.2, derived from Palacky [28], provides observed ranges for various sediments, rock and water-based material.

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**Figure 2.2: Typical ranges in electrical conductivity, \( \sigma \) (S/m), for various earth materials (derived from Palacky [28])**
The electrical conductivity of a material is most significantly a function of the pore space and ore content of the material. In geo-materials such as sands and some rock, the material grains themselves can act as insulating material relative to the pore space fluid (e.g., water saturated sand). The electrical conductivity of the pore space is dependent upon many physical and physiochemical properties such as, salinity, moisture content, temperature, porosity, clay content and rock fracture density. Literature summarizes contemporary theories for the influence of pore space characteristics on measured electrical conductivity (e.g., [10]). Since \( \sigma \) is more dependent upon the pore space electrical conductivity, these techniques are routinely used in petroleum, mining, and hydrological studies including oil/gas location, subsurface cavity location, mineral exploration, down-hole logging, and vadose zone hydrology [11].

Perhaps one of the most significant contributions in modeling the electrical conductivity of porous media can be credited to Archie [29] where the electrical conductivity of the entire porous medium (grains and the pore space) is given by:

\[
\sigma = \left( \frac{1}{\alpha} \right) \phi^m \beta^n \sigma_w
\]  

(2.7)

where \( \phi \), is the porosity, \( \beta \), is the volume fraction of the pore filled with water, \( \sigma_w \) (S/m), is the electrical conductivity of water, and \( \alpha \), \( m \) and \( n \) are constants which range in value depending upon type of grain present:

\[
0.5 \leq \alpha \leq 2.5, \ 1.3 \leq m \leq 2.5, \ n \approx 2
\]  

(2.8)

2.3 Induced Polarization (IP)

While electrical polarization is something to be avoided in DCR, IP methods take advantage of the capacitive behavior of geo-materials. Due to a very large range in \( \sigma \) for any one geo-material (e.g., Figure 2.2; clays span two orders of magnitude), multiple geo-materials can exhibit the same value in electrical conductivity. For example, in Figure 2.2, an electrical conductivity of \( \sigma = 10^{-1} \) S/m could be that of clay, coal, shale or fresh water. Therefore, IP
methods are used in conjunction with DCR methods to further characterize how electricity behaves below the subsurface.

IP methods determine the imaginary component of the well-established complex conductivity, $\sigma^*$ (S/m), shown as:

$$\sigma^* = \sigma' + i\sigma''$$

(2.9)

The real part of complex conductivity, $\sigma'$, is directly related to the electrical conductivity of the pore space fluid (both bulk and surface conductivity; [30]), as well as the presence/concentration of electrically conductive minerals, e.g., metallic ore, sulfides [7], [8]. As either salinity, temperature, degree of saturation, or porosity of the pore space is increased (all else constant), $\sigma'$ is also increased. For example, in highly fractured rock, if the porosity is increased (compared to competent rock) it generally results in an increased $\sigma'$.

The imaginary part of the complex conductivity, $\sigma''$, reflects the ability of the medium to store an electrical charge. Much like a capacitor, as current flows through the material in one direction, charge accumulates to some maximum capacity and eventually current can no longer flow. After current flow is ceased, the medium can then release this charge over time even though the current is shut off. This phenomenon is called the induced polarization effect (IP effect). The IP effect has been attributed to the presence of the electrical double layer most significantly found in clays. Therefore, $\sigma''$, in some instances, may be directly proportional to the clay content [9].

Where DC uses a fixed level of direct current injection over time, IP uses either a) a non-continuous level of DC injection (called time domain IP), or b) continuously injected AC (called frequency domain IP) in order to evaluate $\sigma''$.

In time domain IP, a fixed level of current is injected until some predetermined time and then shut off. The resulting potential response decays over time (even after the flow of current is ceased) as the stored charge is allowed to dissipate. This temporary storage of charge
demonstrates the capacitive effect of the medium. In literature, this is called the ‘chargeability’ denoted as $m_a$ (e.g., [31]):

$$m_a = \frac{v_s}{v_p}$$  \hspace{1cm} (2.10)

where $v_p$ (V) is called the primary voltage (the voltage measured during the injection of fixed current), and $v_s$ (V) is called the secondary voltage (the voltage measured immediately after the shut off of current). Because the secondary voltage is a time-dependent and variable response, an alternate equation is often introduced to account for the averaged, total (integral) decay of voltage over time:

$$m_{a\text{avg}} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} V(t) dt$$  \hspace{1cm} (2.11)

where $V(t)$ is the time dependent potential measured, integrated over the total decay time, $t_1$ to $t_2$. Figure 2.3 displays an example of what this relationship might look like.

**Figure 2.3: Time domain induced polarization measurement [32]**

In frequency domain IP, AC is injected at some specific frequency, $f$ (Hz). As the current oscillates between maximum and minimum amplitudes, the voltage response will also oscillate.
If a material exhibits a capacitive nature, then a phase difference (\( \Phi \)) will exist between the current and the voltage response (Figure 2.4) where the voltage lags the injected current.

\[ V(\text{Volts}) \]
\[ I(\text{Amps}) \]
\[ \text{time} \]

**Figure 2.4: Frequency domain induced polarization (phase difference, \( \Phi \))**

Some geo-materials exhibit a frequency dependent IP response where at different injected current frequencies the measured voltage phase difference is subject to change. Therefore, materials can be further classified when a range in frequencies is used – each injected one at a time (between 1mHz-1GHz). This practice is called spectral induced polarization (SIP). There exist many theories for the interpretation of the SIP relationship to pore space characteristics ([33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]). One theory considers frequency dependent polarization mechanisms called grain polarization and electrolytic polarization ([4], [44], [45]).

Grain polarization (Figure 2.5(a)) results from an internal blocking of a continuous porous pathway by an electrically conductive grain. Since charges cannot flow past this grain easily, they become concentrated at the blockage and will simulate an electrical resistance to flow. When current flow is ceased, the charges return back to their neural state and simulate a release in charge across the grain.
Electrolytic polarization can occur from two different situations. The first (Figure 2.5(b)) is due to the presence of a throat/constriction within the continuous pore space where negatively charged grains are present (e.g., clay). In this instance, positive charges (adsorbed onto the grain surface) may restrict the flow of negative charges. The second (Figure 2.5(c)), shows negatively charged clay or fibrous grains along the sides of a flow channel. These negatively charged grains attract positive ions and tend to restrict the flow of negative charges when the density of positive charges is too great.

The frequency dependent resistance or impedance, $Z(\omega)$, is related to the frequency dependent voltage, $V(\omega)$, and the frequency dependent current, $I(\omega)$, by Ohm’s law (frequency dependent):

$$Z(\omega) = \frac{V(\omega)}{I(\omega)}$$  \hspace{1cm} (2.12)
The impedance is converted to an electrical conductivity and corrected through a geometrical factor (e.g. [42]). Given the injected current frequency, \( \omega \) (rad/s), the magnitude of the conductivity, \( |l\sigma| \), and the phase, \( \Phi \), in frequency-domain IP are mathematically related to the real (in-phase, \( \sigma' \)) and imaginary (out-of-phase, \( \sigma'' \)) components of the complex conductivity (\( \sigma^* \)) (e.g., [46]) according to:

\[
\sigma^* = |\sigma| \exp(i\omega) = \sigma' + i\sigma'' \tag{2.13}
\]

\[
|\sigma| = \sqrt{\sigma'^2 + \sigma''^2} \tag{2.14}
\]

\[
tan\Phi = \frac{\sigma''}{\sigma'} \tag{2.15}
\]

Equation 2.14 and Equation 2.15 show that the amplitude and phase, \( |l\sigma| \) and \( \Phi \), are both dependent upon the conductive properties of the material (through \( \sigma' \)), as well as its capability to store charge (through \( \sigma'' \)).

In many exploration applications, and specifically in time dependent applications, SIP is not effective because the full spectral measurement process can take tens of minutes (or hours) to achieve measurements across a range in frequencies. This is especially true at lower frequencies (mHz levels) where a 1mHz current injection requires nearly 17 minutes for one period of oscillation. The percent frequency effect (PFE) measure has been widely used as a compromise to resolve some information about frequency dependence and avoiding longer measurement cycles [3], [4], [11], [47]. Recall the introduction of PFE from Chapter 1 using electrical resistivity as opposed conductivity presented here.

Two frequencies, \( f_{DC} \) and \( f_{AC} \), are injected one at a time and their respective conductivity amplitudes, \( |\sigma_{DC}| \) and \( |\sigma_{AC}| \), are compared by Equation 2.16.

\[
PFE(\%) = 100 \left( \frac{|\sigma_{AC}| - |\sigma_{DC}|}{|\sigma_{DC}|} \right) \tag{2.16}
\]

Where \( |\sigma_{DC}| \) and \( |\sigma_{AC}| \) are the magnitudes of measured electrical conductivity for injected current at frequencies of \( f_{DC} \) and \( f_{AC} \), respectively. \( f_{DC} \) and \( f_{AC} \) are user defined and are subject to change between applications. Typically, \( f_{DC} \) represents a low frequency (defined as 20Hz for
BEAM systems in Chapter 1) that simulates DC current injection (on the order of Hz) and \( f_{AC} \) is some frequency that respects \( f_{AC} > f_{DC} \) (on the order of 100's of Hz; 200Hz for BEAM systems in Chapter 1).

PFE is a common method for characterizing the imaginary component of complex conductivity, however is offers some limitations in uniquely defining material type. Within the last decade or so, geophysics literature has focused significantly on evaluating geo-materials using SIP methods, which evaluate the imaginary component across a range in frequency as opposed to only two frequencies [40], [41], [42], [43]. For example, Revil et al. [48] investigates how the phase difference between injected current and measured voltage can be uniquely correlated to some unsaturated soils for a frequency range between 1mHz and 1GHz.

2.4 Surface-Based Implementation

Traditional surface-based applications, utilize a set of four metallic electrodes (typically stainless steel), called A, B, M, and N (Figure 2.6). In DC methods, current, \( I \), (on the order of tens of mA) is injected through electrode A and is retrieved by electrode B. The voltage, \( V_{MN} \), is measured as a difference in potential between electrodes M and N. In frequency domain IP methods, the role of current injection and retrieval of current oscillates between A and B as the amplitude of current continuously oscillates between positive and negative as illustrated from Figure 2.4.

Figure 2.6 shows an arbitrary electrode spacing, however many electrode configurations exist in literature and practice (e.g. Wenner, Dipole-Dipole, Schlumberger), and are used in various situations for either increased depth of current penetration or increased spacial resolution in near surface geophysics. For example, a Wenner array is typically used for increased resolution near the surface, whereas a Schlumberger array is typically used to achieve information at greater depths ([10], [11]). Figure 2.7 illustrates a handful of the most well-known surface-based electrode arrays.
Figure 2.6: Classical generic surface resistivity array

Consider Figure 2.8 for an electrical current point source at the surface of a homogeneous and isotropic half-space. Given equal conductance for current flow within the half-space, lines of equal current density, $J \, (A/m^2)$, can be drawn at hemi-spheres and the current density is inversely proportional to the distance, $r \, (m)$, away from the current point source and $2\pi r^2$ is the surface area of a hemisphere:

$$J = \frac{1}{2\pi r^2} \quad (2.17)$$

The electrical potential, $\Psi \, (V)$ is written in terms of Ohm’s law as:

$$\Psi = \frac{1}{2\pi r\sigma} \quad (2.18)$$

Equation 2.18 can also be written in terms of the level of current injected/retrieved by electrodes A and B, the electrical conductivity of the homogeneous subsurface, and the relative spacing between the four electrodes:

$$\Psi = \frac{1}{2\pi\sigma} \left[ \frac{1}{AM} - \frac{1}{(MN + NB)} - \frac{1}{(AM + MN)} + \frac{1}{NB} \right] \quad (2.19)$$
In literature, this equation is simplified by introducing the geometric factor, $K$ (m). As the current injection/retrieval level is user defined and the potential is measured across electrodes M and N, then the electrical conductivity of the homogeneous material may be identified through Ohm’s Law:
where $\sigma_a$ (S/m) is called the ‘apparent’ conductivity and $V_{MN}(V)$ is the potential difference that can be expressly written as a difference in potential between electrodes $M$ and $N$. In nearly every case, a subscript ‘$a$’ on the electrical conductivity specifies that the measured value is apparent because of the likelihood for heterogeneities (e.g., soil and rock stratifications) but is not captured in a single measurement with four electrodes.

Equation 2.20 observes the value of $K$ to be dependent solely upon the geometry of the relative electrode spacing for an infinite half space. Chapter 3 will identify this analytical process to be only functional for simply geometries and boundary conditions. With recent advancements in numerical modeling through the use of partial differential equations, $K$ can be computationally identified given complex geometries and boundary conditions. This advancement is extremely advantageous for complicated systems, for example, in the field of tunneling where TBMs of various sizes and types can be integrated into $K$ to provide a more unique prediction of the geomaterials in front of the tunnel face.

The depth of current injection is proportional to the separation distance between injection electrodes (A and B) and the spatial distribution on electrical conductivity. Given a homogeneous medium in an infinite half space, the flow of electrical current is solely dependent upon the electrode spacing. This will be a main topic of discussion in Chapter 6 when the TBM tunneling environment provides a number of other complexities that influence how current flows in front of and around the TBM/tunnel. For a given four electrode spacing, a single measurement of $\sigma_a$ is taken and given a rule-of-thumb estimated location below the subsurface at a point ‘$P$’ (Figure 2.9a). In Figure 2.9(c), an array of electrodes can be used, four at a time, in order to develop a two dimensional cross section of apparent conductivity measurements.
The spatial resolution of electrical conductivity measurements is inversely proportional to the relative spacing between electrodes A and B (typically between 1 and 10 meters), where resolution decreases for increases in spacing and vice versa. At best, existing surface-based electrical methods can achieve a spatial resolution on the centimeter scale [10].

![Image of four electrode array and typical dimensions of stainless steel stake used for surface-based measurements.](image)

**Figure 2.9:** (a) Rule of thumb estimation for location apparent conductivity measurement at Point ‘P’, (b) typical dimensions of stainless steel stake used for surface-based measurements

In theory, the four electrode array is idealized by four points with no physical properties or influence on the electrical physics of the surrounding environment. In reality, the four electrodes do have material properties and do have influence on the electrical physics of the surrounding environment. When the electrodes are made of iron alloy, such as steel, the electrodes themselves can become electrically polarized and demonstrate an IP effect. As the
steel electrode is polarized its contribution to the IP Effect is far greater than that of the surrounding earth. Therefore, when measuring the IP effect of the surrounding earth, the measurements will be inaccurate as the polarization of both the electrode and the earth are captured. A non-polarizing metal, such as silver/silver-chloride (Ag-Ag/Cl) is used to eliminate the contribution from the electrodes on the measured IP Effect [47]. However, this type of electrode can be expensive to implement. Instead, steel spikes (Figure 2.9b) are used with the injection of DC current only, where the IP effect is neglected and not captured. Using DC methods only is not ideal as it will not fully characterize $\sigma^*$. However, in some instances, the imaginary component of the complex conductivity is much less than the real part, $(\sigma^*<\sigma)$ [18]. Therefore, the phase difference between the injected current and the measured potential is relatively zero and $\sigma \approx \sigma^*$. This is especially true for larger grain materials like sands and gravel.

The following discussion will analyze a simple surface-based electrical resistivity array. Figure 2.10 shows four simple conductivity situations that could be present below the surface. These four different situations are analyzed and compared to establish a framework for the extension to the TBM tunneling environment.

Figure 2.10(a) illustrates the case where the earth is assigned a homogeneous electrical conductivity, $\sigma = 10^{-2}$ S/m. The voltage measured between electrodes M and N is $V_{MN} \approx \frac{14}{a} V$. In Figure 2.10(b), the electrical conductivity of the earth is uniformly increased by a factor of 10 to the condition where $\sigma = 10^{-1}$ S/m. In comparison to Figure 2.10(a), there exist no differences in the flow of electrical current through the earth. Since the electrical conductivity is homogeneous in both cases, the path of current flow must remain identical as it has no alternative medium through which to flow. The distinction between Figures 2.10(a) and 2.10(b) lies in $V_{MN}$. Due to the increase in electrical conductivity by magnitude of 10, the voltage decreases by the same magnitude according to Ohm’s Law. The measured voltage in Figure 2.10(b) is $V_{MN} \approx \frac{14}{a} V$.

There are two consequences to the resulting voltage measured in Figure 2.10(b):
1. A decrease in resolution

2. A decreased signal to noise ratio under the assumption of equal noise amplitudes.

Figure 2.10: Slice of a three-dimensional, surface-based, electrical resistivity (DC) Wenner array. Current flow (%), equipotential lines (V) and current density contours (mA/m²), for the electrical conductivity structure given by (a) homogeneous $\sigma = 10^{-2}$ S/m, (b) homogeneous $\sigma = 10^{-1}$ S/m, (c) infinite, horizontal planar difference for $\sigma_1 = 10^{-2}$ S/m (top layer), and $\sigma_2 = 10^{-1}$ S/m (bottom layer), and (d) infinite, horizontal planar difference for $\sigma_1 = 10^{-1}$ S/m (top layer), and $\sigma_2 = 10^{-2}$ S/m (bottom layer).

Figures 2.10(c) and 2.10(d) show the cases where one homogeneous material overlays a different homogeneous material (e.g. a transition in geology or presence of groundwater). As shown, the planar difference occurs at a depth of $z = a$. The plane could exist at any depth and will be discussed later in this section.

The first layered scenario is presented in Figure 2.10(c) where the top earth layer has a lower electrical conductivity than the bottom earth layer (e.g. sand on top of clay or unsaturated
soil/rock overlying saturated soil/rock). The electrical current is more attracted to the bottom layer and current will penetrate to greater depth in order to reach the more conductive medium than for a completely homogeneous case (Figure 2.10(a)). In Figure 2.10(c), 15% of the total current reaches the interface of the two layers as opposed to the 37% observed in Figures 2.10(a) (or Figure 2.10(b)) at the same depth. Accordingly, a majority (85%) of the current flows within the bottom layer. The voltage between electrodes M and N is marginally less than that for Figure 2.10(a) \(V_{MN} \approx \frac{11}{a}V\) in Figure 2.10(c) compared to \(V_{MN} \approx \frac{14}{a}V\) in Figure 2.10(a). The presence of the conductive bottom layer reduces the measured voltage because the electrical conductivity observed by the electrode array has increased on average when compared to the homogeneous case in Figure 2.10(a). By Ohm’s Law, the measured voltage must decrease given an increased electrical conductivity. As the difference moves closer to the surface the average conductivity will continue to increase, whereby the measured voltage will continue to decrease. This result is shown in Figure 2.11 and is discussed later.

The second layered scenario is shown in Figure 2.10(d) where the top layer has a greater electrical conductivity than the bottom layer. The electrical current flow is mostly (80%) confined to the conductive top layer. The voltage between electrodes M and N here is slightly greater than Figure 2.10(b) \(V_{MN} \approx \frac{2.0}{a}V\) in 2.10(d) compared to \(V_{MN} \approx \frac{1.4}{a}V\) in 2.10(b)). Due to the presence of a resistive lower layer, the average electrical conductivity is decreased when compared to the homogeneous case in Figure 2.10(b) and the measured voltage must increase.

In reality, current flow lines do not exist and are only shown here to help illustrate the spatial distribution and direction of current flow. In three-dimensional space, the amount of current at any point of interest is represented by a current density given by the magnitude of current passing through a unit cross-sectional area. Mathematical models for percentage of current have been developed for simpler geometries like a horizontal planar difference shown in Figures 2.10(c) and 2.10(d). When models are given more complex geometries and a range of
electrical conductivities, analytical techniques that define percent current are not well-established, and so, analysis must be administered by computational approaches (e.g., finite element, finite difference) that provide current densities rather than current percentages. Current density contour levels and associated maximum penetration distances of $z_{\text{max}}$ are shown in Figure 2.10 for values of 5, 1 and 0.5 A/m$^2$.

For a given depth of $z$, the percentage of the total injected current behaves similarly to $z_{\text{max}}$. This is conveyed by the current density contour levels. For example, Figures 2.10(a) and 2.10(b) show identical current percentages for any value of $z$. Likewise, current density contours and corresponding values for $z_{\text{max}}$ are also identical between Figures 2.10(a) and Figure 2.10(b). When current penetrates deeper, as shown in Figure 2.10(c), the same current density contours also penetrate deeper and are shown with increased $z_{\text{max}}$ values. Therefore, when quantifying the amount of current in a three dimensional space, this dissertation will utilize current density because it is analogous to percent current.

The cases shown in Figures 2.10(c) and 2.10(d) illustrate a horizontal planar difference at a depth of $z = a$. However, this planar difference could exist at any depth. Figure 2.11(a) shows $V_{MN}$ as a function of the depth of the planar difference. The results from both layered scenarios are presented; Figure 2.10(c) and Figure 2.10(d). A bold, dashed line is shown for the scenario where the planar difference is located at a depth of $z = a$. Figure 2.11(a) shows how the measured voltage changes as the planar difference is shifted with respect to the surface. As $z/a$ is increased, $V_{MN}$ tends to a constant value where the underlying layer has no influence on $V_{MN}$, and $V_{MN}$ equals the value of the corresponding homogeneous case (Figures 2.10(a) and 2.10(b)). When extended to the TBM tunneling environment, this condition is referred to as the far-field condition or $V_{\text{FAR FIELD}}$. 
Figure 2.11: Surface-based, Wenner \( (a = 20\text{m}) \) electrical resistivity array, (a) voltage measurement, \( V_{MN} \), for various depths, \( z/a \), of the infinite, horizontal planar difference: \( \sigma_1 = 10^{-2} \text{ S/m}, \sigma_2 = 10^{-1} \text{ S/m} \) and \( \sigma_1 = 10^{-1} \text{ S/m}, \sigma_2 = 10^{-2} \text{ S/m} \) (b) sensitivity curves \( (V_{MN} - V_{\text{FAR FIELD}}) \) for various depths, \( z/a \), of the infinite, horizontal planar difference: \( \sigma_1 = 10^{-2} \text{ S/m}, \sigma_2 = 10^{-1} \text{ S/m} \) and \( \sigma_1 = 10^{-1} \text{ S/m}, \sigma_2 = 10^{-2} \text{ S/m} \)

As the planar difference is moved closer to the surface \( (z/a \to 0) \), \( V_{MN} \) changes non-linearly. At some location of the planar difference, if \( V_{MN} \) records a change in voltage relative to the far-field condition, then the electrode array is considered sensitive to the planar difference for any distance less than or equal to its present \( z/a \) location. Plots in the remainder of this dissertation present the change in voltage \( (\Delta V = V_{MN} - V_{\text{FAR FIELD}}) \) as opposed to absolute measured voltage. In Figure 2.11(b), for the condition where \( \sigma_1 = 10^{-2} \text{ S/m}, \sigma_2 = 10^{-1} \text{ S/m} \), the electrode array is considered sensitive at a depth less than or equal to \( z/a \approx 4 \). In Figure 2.11(b), for the condition where \( \sigma_1 = 10^{-1} \text{ S/m}, \sigma_2 = 10^{-2} \text{ S/m} \), the electrode array is considered sensitive at a depth less than or equal to \( z/a \approx 2 \). Therefore, the array is considered more sensitive to an incoming conductive layer than an incoming resistive layer.

Computational analysis provides a noise free environment to observe these trends. In practice, electrical noise will be present and can affect the ability of an electrode array to detect differences like those shown in Figure 2.10. It is expected that electrical noise will limit the
predication ability of electrical resistivity and is likely site specific regarding its
magnitude/fluctuation.

2.5 Borehole-Based Implementation

The need for high spatial resolution (cm scale) data at greater depths (>50 meters)
motivated the oil and gas industry to develop borehole-based techniques in the early 1900's
using the Schlumberger methods for well logging (e.g., [6], [12], [49]). In contrast to surface
based-methods, borehole-based methods can achieve continued high spatial resolutions at
greater depths because of the ability to position electrodes at any interval along the depth of a
borehole (typically 10 cm in diameter and sometimes up to 15 cm in diameter; e.g., [50]). Some
of the earliest borehole-based methods utilized a four electrode array similar to the
aforementioned surface-based methods. Figure 2.12(a) shows a traditional (called unfocused
methods; [49]) A, B, M and N configuration applied to a vertical borehole, where three
electrodes (A, M and N) are confined to a housing unit and are restricted in movement relative
to one another. The fourth electrode (B) is located at a fixed point on the earth surface. The
electrode housing is lowered into a previously drilled borehole, where it is successively moved
to image different horizons.

Using so-called ‘current focusing’, the four-electrode implementations were soon
advanced to increase the spatial resolution of measurements, increase current penetration
distance, and most importantly mitigate adverse ‘borehole effects’ (Figure 2.12(b)). The most
significant borehole effects include the undesired absorption of electrical current from the
addition of (a) electrically conductive mud to increase the contact between the earth and the
electrodes, and from (b) metallic borehole casings used to increase borehole structural stability.
These two effects will be discussed in the following paragraphs.

In a case where a dry borehole exists (no borehole fluid, e.g. bentonite slurry), the
electrical contact between an electrode and the earth (borehole sidewall in this case) can be
poor, and as a consequence current injection into the earth is substantially reduced. To improve
electrical contact, clay-mud is injected into the borehole to help improve the electrode contact with the earth. In unfocused methods (Figure 2.12(a)), this solution can lead to additional problems, especially when mud with higher salinity, and therefore higher conductivity, is used [51]. In these cases, current may actually remain confined within the more conductive mud and travel up the borehole sidewall (Figure 2.12(a)).

Since the initial development of focused arrays for borehole applications, many unique methods for focusing have been manufactured for commercial use (Laterolog LLS, Laterolog LLD, HRLA Dual Laterolog etc.). Figure 2.12 shows an earlier approach (patented by Vinegar and Waxman 1986 [52]) to ‘current-focusing’ using guard injection electrodes (Figure 2.12(b): $A_1'$ and $A_2'$) instead of a single injection electrode (Figure 2.12(a): A). Each guard electrode injects a separate stream of current. The additional current from the guard electrodes, $A_1'$ and $A_2'$ are adjusted, automatically and independently, such that the voltage difference between sets $M_1$ and $M_1'$ and also $M_2$ and $M_2'$ is zero. This zero voltage situation creates the condition where no current is able to flow through the borehole. Therefore, the survey current from injection electrode A is forced out into the earth.

Traditionally, borehole-based electrical methods are used in uncased boreholes, where direct electrical contact between the earth and the electrodes is possible. In many applications over recent years, boreholes are cased to prevent collapse of the borehole. Due to the large difference in conductivity between steel casing and the earth (on the order of $10^6$ S/m), it is very difficult to propagate current into the earth without it flowing directly through the casing and back to the retrieval electrode (Figure 2.12(a)), even with focused arrays like the one in Figure 2.12(b). Early research has explored the idea of measuring very small electrical potential changes due to a very small amount of current propagation into the earth, whenever a metallic casing is present [52]. Early applications were not yet feasible until recent advances in modeling and measurement sensitivity. Numerical and experimental studies have shown success in electrical methods using cased boreholes [54], [55], [56], [57].
Noise is always a consideration when taking a measurement for any type of investigation. For DCR and IP methods, noise is introduced almost entirely by voltage measurements (or so-called stray currents). Voltage noise can be introduced in a few different ways. One example is from the natural electrical field in the earth, which is transient. A given measurement of an induced electric field created by forced current flow may not be constant as the electrical field in the earth is constantly changing.

A second possible source of error is created from the resolution of the voltage measurement itself. While there are always advancements in voltmeter precision (mV in Kaufman [54]), the true voltage value for any given measurement may be inaccurate by up to half of the sensitivity (for example, a true voltage measurement of 19.6 mV, may be read as 20 mV by the instrumentation). Therefore, an error of 0.4mV has occurred in the measurement process.
In order to overcome sources of errors or noise, according to Milsom and Erikson [58], surveys are encouraged to employ larger signals (i.e. increased current injection) in order to create a higher signal to noise ratio. Furthermore, by their own nature, certain electrode arrays will create larger signals. In certain situations, the Schlumberger electrode array is one example that can achieve signals which are three times greater than signals with equal amplitudes of current injected in a Wenner array [58].
CHAPTER 3
LABORATORY SCALED MODEL TESTING FOR THE PREDICTION OF A METAL PIPE OR ROD AHEAD OF THE TUNNEL BORING USING ELECTRICAL RESISTIVITY THEORY

3.1 Introduction

This chapter presents an experimental study of a scaled model \( D = 6.3 \text{cm} \) TBM as it excavates through a poorly graded saturated sand and uses electrical resistivity methods to predict an incoming metallic pipe (OD = 1.3cm, ID = 1cm) or rod (OD = 1.3cm). Using two integrated electrical resistivity arrays that mimic commercially available systems, this study analyzes how far ahead of the tunnel face the electrode array can predict the incoming pipe or rod. Detailed discussion is given for the construction of the experimental setup including the design of the scaled TBM, the dimensions of the tank used to contain the experiment. This chapter also details an experimental/computational study for the evaluation of electrical conductivity of the saturated sand used in the tank as well as a computational study, which compares the experimental results to a 1:1 scale finite element model.

3.2 Experimental Scaled TBM and Tank Design

The scaled TBM constructed for these experiments models a full scale TBM as a copper metal cap fastened on the end of a hollow PVC tube. The final design of the TBM is shown in Figure 3.1 with a computer generated image with dimensions (Figure 3.1(a)) and the real scaled TBM (Figure 3.1(b)).

The 6.3cm diameter TBM is constructed of a copper cap to emulate the cutterhead and shield. Even though the cutterhead independently rotates with respect to the shield in the field, it is expected that these two components are not perfectly electrically isolated from one another [59]. Attached to the face of the cutterhead are nine symmetrically placed ‘cutting tools’, which are disks made of silver/silver-chloride (Ag/Ag-Cl) (diameter of 4mm and height of 1mm). Ag/Ag-Cl is a commonly used material for electrical (electrical resistivity and induced polarization)
surveys as it is electrically non-polarizing and thereby ensures that the electrodes themselves do not contribute to the measured electrical signal. Each Ag/Ag-Cl electrode is glued to a neoprene rubber washer and then glued to the face of the cutterhead in order to ensure electrical isolation from the copper cutterhead. Even though applied here in a laboratory setting, non-polarizing electrodes (e.g., Ag/Ag-Cl) are not yet feasible in the field as they are expensive and too soft to survive in the harsh tunneling environment.

Figure 3.1: Isometric view of laboratory scaled tunnel boring machine (TBM) equipped with electrical resistivity electrode array (a) computer generated with dimensions and labels, (b) actual model

Behind the TBM, a concrete tunnel lining is represented by a hollow schedule 30 PVC tube with a diameter equal to the TBM. The electrical conductivity of actual concrete can vary
between $10^{-4}$ and $10^{-8}$ S/m [60] depending upon the material makeup of the concrete and the concentration of rebar or other reinforcing materials. PVC holds an electrical conductivity of about $10^{-14}$ S/m and so will significantly underestimate the conductivity of the tunnel lining. It is not expected that this difference will meaningfully influence the experimental results since both concrete and PVC act as relative insulators in this environment. This idea is confirmed in computation modeling performed in Chapter 4, which analyzes the so-called interface region for various TBM types.

Along the lining and behind the TBM, there are two 1.9cm wide brass rings that are secured around the circumference of the tunnel. The ring closest to the TBM is used for potential measurement (electrode N) and the other is used as a current sink (electrode B). This is not consistent with typical point reference electrodes in the field; however, this feature can be captured through modeling and aids to ensure symmetry of the experimentation.

A polypropylene plastic tank was designed and created for the experiments to hold the saturated sand for the TBM to excavate through. The goal of the tank is two-fold:

1. Be large enough as to mitigate unwanted electrical boundary effects of current flowing around the model TBM/tunnel.
2. Hold a controlled saturated sand through which the TBM can excavate toward an anomaly of known location.

A key question in sizing the tank was, how large does the tank need to be in order to mitigate any undesired boundary effects? To evaluate the appropriate size of the tank, the finite element suite called COMSOL Multiphysics was used. COMSOL uses physics-based partial differential equations to model the influence of physical phenomenon (e.g., acoustic wave propagation, water transport through porous media, etc.) on user-defined geometries and materials. The equations used within the software are based on those presented in Chapter 1 for current flow in three dimension space.
The dimensions that define the tank size are shown in Figure 3.2 as $R_{TANK}$ and $H_{TANK}$. The center of the cutterhead face ($x,y,z = 0,0,0$) is held at a height of 26.5cm from the bottom of the tank and is vertically centered within the tank at $x,y = 0,0$. The TBM elevation of 26.5cm is somewhat arbitrary at this point in the study, but is used later as a limit of TBM progression toward a metal pipe (or rod) in the laboratory experimentation.

Figure 3.2(a) shows a side view of the finite element model setup including the laboratory scaled model TBM from Figure 3.1. The potential measuring electrodes M and N are not included in this model space. Instead, discrete points are used to query the model space ahead of the TBM as shown in Figure 3.2(b). As opposed to a voltage measured by the difference in potential between electrodes M and N, a point of information yields an electrical potential, $\Psi$, since it is not referenced to another measure of electrical potential. By itself, this measurement is meaningless in reality but can be used here for a relative comparison of data. In COMSOL a point of $\Psi$ is ‘referenced’ to the insulating boundary condition (i.e., $\Psi = 0$) in order to determine a numerical value.

All external boundaries in the finite element model space are defined as insulating boundaries, which means that no electrical current is allowed to escape the defined geometry of the model. These boundary conditions are important as they are most representative of laboratory conditions where air surrounds the tank (i.e. no current transfer to air).

The geometries (tank, sand, and TBM) in Figure 3.2 are meshed with tetrahedral elements. The current source and sink are meshed very finely with minimum and maximum element sizing of 0.4mm and 1mm, respectively. Since it adjoins the current sink and source geometries, the PVC tunnel lining is given the same minimum element size of 0.4mm, but its maximum is raised to 5mm to increase computational speed. The air inside the TBM/lining geometry is meshed with 5mm/30mm as their min/max element sizing. Since the remainder of the model (sand and tank) is relatively large, it is given minimum and maximum sizing of 2.5mm and 25mm, respectively. A meshing parameter called “element growth rate” is held constant at
1.3 to increase mesh quality. This parameter defines that an element cannot be 1.3 times larger or smaller than an adjacent element. The meshing parameters presented here are identical to those for the models presented in Section 4 of this chapter.

Figure 3.2: Finite element model design of laboratory scaled \( D = 6.3 \text{cm} \) TBM in plastic tank for the evaluation of \( \text{RTANK} \), \( \text{HTANK} \) and \( \text{HTBM} \) (a) side view of tank/TBM dimensions, (b) side view of TBM with discrete measurement points in front of TBM for various values in \( z \) \((x,y) = 0,0\))

The electrical conductivity of the soil inside of the tank is arbitrarily set at \( \sigma = 10^{-1} \text{ S/m} \) and is inconsequential to the conclusions drawn for the boundary condition analysis (i.e., a change in the soil conductivity causes a scaled change in electrical potential in accordance with Ohm’s law but does not influence conclusions drawn for this study on boundary conditions).

Electrical current is injected and retrieved at an amplitude of 5mA. The reader should note here that the average current density flowing from the entire TBM body is approximately 381 mA/m². This current density is somewhat higher than current densities observed in computational models detailed in the following chapters for a full-scale TBM.

The idea for sizing the appropriate tank is holding one tank dimension constant and varying the other until an equilibrium condition is met. Here, the equilibrium condition is met
when there is relatively no change in $\Psi$ for an incremental increase of the tank size. For a combination of $R_{\text{TANK}}$ and $H_{\text{TANK}}$ the corresponding potential, $\Psi(\text{mV})$, is measured at the front and center of the cutterhead ($x,y,z = 0,0,0$) and for a series of distances, $z(\text{m})$, in front of the TBM ($x,y = 0,0$) (Figure 3.2(b)) from 0 to 10cm. The evaluation of potential at numerous points serves the purpose to verify that the boundaries of the tank do not influence the flow of current beyond the boundaries of the TBM. The results in Figure 3.3 verify this.

Figure 3.3(a) shows five curves of $\Psi(\text{mV})$ vs. $R_{\text{TANK}}$ for the five discrete points of $z$ and a constant $H_{\text{TANK}} = 1\text{m}$. The curves show two behaviors:

1. The curves do not overlap one another. Each value of $z$ yields a different value of $\Psi$ for a single value of $R_{\text{TANK}}$. This is to be expected. Recall from Chapter 2 that as current flows away from the source (or toward the sink), the electrical potential will continue to drop. The curves in Figure 3.3(a) verify this.

2. Each curve achieves the equilibrium condition at the same value of $R_{\text{TANK}} = 0.5\text{m}$. This implies that the electrical current uniformly fills to the space provided up to $R_{\text{TANK}} = 0.5\text{m}$ and any increase in $R_{\text{TANK}}$ does not supplement current flow as it is confined by another geometry - in this case $H_{\text{TANK}}$. Chapter 5 details the influence of several geometric conditions that affect electrical behavior and will evaluate how boundaries, such as the ground surface, can significantly influence how current is distributed in front of the TBM.

In order to examine the influence of $H_{\text{TANK}}$, $R_{\text{TANK}}$ is set at 0.5m. Figure 3.3(b) shows five curves of $\Psi(\text{mV})$ vs. $H_{\text{TANK}}$ for the five discrete points of $z$ for a constant $R_{\text{TANK}} = 0.5\text{m}$ and $H_{\text{TM}} = 0.265\text{m}$, where the TBM is concentric with the cylindrical tank. Again, the plot shows that the curves in $\Psi$ do not overlap each other and also decrease in value as $z$ increases. This observation is expected as the current density is expected to decrease as $z$ increases further from the current source according to Ohm’s law. At a value of $H_{\text{TANK}} \approx 0.7\text{m}$, the equilibrium condition is met for all curves. In contrast to the curves presents for the evaluation of $R_{\text{TANK}}$, the curves for $H_{\text{TANK}}$ sharply rise as beginning at $H_{\text{TANK}} \approx 0.4\text{m}$ until the equilibrium condition $H_{\text{TANK}} \approx 0.7\text{m}$. The results in Figure 3.3 verify this.
0.7m. This sharp increase (i.e., for \( z = 0 \): \( \Psi \) rises about 1V over a span of \( H_{TANK} \) of 0.25m) would suggest that \( H_{TANK} \) has a strong influence in boundaries conditions for the flow of electrical current.

Figure 3.3: \( \Psi (\text{mV}) \) vs. (a) \( R_{TANK} (H_{TANK} =1\text{m}) \) and (b) \( H_{TANK} (R_{TANK} = 0.5\text{m}) \) (c) \( H_{TBM} (R_{TANK} = 0.5\text{m}, H_{TANK} = 0.66\text{m}) \)

Figure 3.4 shows the final tank design used for the experimental TBM look-ahead study. A final \( R_{TANK} = 0.5\text{m} \) and \( H_{TANK} = 0.66\text{m} \) was used for dimensions of the tank. The slightly decreased \( H_{TANK} \) of 0.66m was chosen based upon the availability of materials. The tank is filled
with a saturated sand with an electrical conductivity of approximately $10^{-2}$ S/m. The following section will describe how the electrical conductivity of the saturated sand is evaluated.

![Figure 3.4: Experimental tank, $R_{TANK} = 0.5m$ and $H_{TANK} = 0.66m$ filled with a saturated sand (a) isometric view, (b) side view](image)

Another consideration was given regarding the location of the TBM relative to the top/bottom of the tank. In order to verify that altering the location of the TBM within the tank was not relevant to the measured voltage change when the TBM approaches the pipe or rod, a similar computational study was performed by moving the TBM along the z-axis within the expected range for laboratory experimentation (i.e., $H_{TBM}$ range between 0.26 and 0.46m).

Figure 3.3(c) shows a plot of measured potential at the point $x,y,z = 0,0,0$ on the face of the TBM for the tank design dimensions. The plot shows that $\Psi$(mV) does not significantly change when $H_{TBM}$ changes. A slight increase from $\Psi = 0.48$mV to $\Psi = 0.59$mV when $H_{TBM}$ increases from 0.425m to 0.46m. Since the sink electrode is very close to the surface of the tank (insulating boundary), a boundary effect increases $\Psi$ at the TBM face even though no anomaly is present within the tank. This boundary effect is a consideration in laboratory methods, but did not seemingly play a role in the ability to detect the metal pipe or rod during experimentation. These details are addressed at the end of the chapter.
3.3 Evaluation of Saturated Sand Conductivity

The electrical conductivity of the saturated sand was evaluated through two custom built experimental studies. Each of the experimental studies are validated through computational modeling to ensure the accuracy and validate the experimental results.

3.3.1 Experimental and Computational Validation Using a Capsule

The first evaluation method used an in-house constructed capsule shown illustrated with dimensions in Figure 3.5. The capsule is built from a hollow acrylic tube (ID = 7.6cm, 0.6cm wall thickness). On either side of the acrylic tube, a stainless steel piston (OD = 7.6cm, H = 3.8cm) is inserted to contain the specimen. The two pistons are also used for current injection and current retrieval. To measure the induced voltage, two stainless steel screws were inserted through the side walls of the acrylic tube – each 11.4cm from either side of the cell.

![Diagram of capsule with dimensions](image)

**Figure 3.5: Dimensions of the capsule used for the evaluation of electrical conductivity of saturated sand**

The four electrodes (A, B, M and N) were connected to a terrameter (Figure 3.6(a)) in order to take the electrical resistivity measurement. The terrameter measures a total conductance, $S(S)$, of the material inside of the capsule since the terrameter is unaware of the geometry of the measurement taken. In order to evaluate $\sigma$ (S/m) for the material property per meter of material, the so-called geometrical factor $K$ (m) is needed for this specific capsule design. Much like with surface based electrical resistivity arrays (discussed in Chapter 2), each electrode array presents its own geometrical factor and is based upon the relative electrode
spacing and the boundary conditions of the measurement (e.g., an infinite half space of a surface-based electrode array).

As opposed to a simplistic surface-based electrode array, mathematical models do not yet exist which can evaluate the geometrical factor of more complex electrode arrays and boundary conditions such as that of the capsule. The geometric factor of the capsule can be evaluated through either experimental or computational analysis. Both are used in literature and so this study will use both to verify each other.

![Experimental setup for electrical conductivity capsule measurement](image)

**Figure 3.6**: Experimental setup for electrical conductivity capsule measurement; (a) capsule wired to electrical resistivity meter (terrameter), (b) close-up of electrical conductivity capsule showing electrodes A and B (stainless steel plates), electrode M and N (stainless steel screws)

For experimental evaluation, the capsule is filled with tap water of known electrical conductivity. A specified and arbitrary amplitude of current (5mA) is injected and retrieved
through electrodes A and B. The corresponding $V_{MN}$ is measured across electrodes M and N.

Through equation 3.1, $K$ can be calculated:

$$K = \frac{I}{\sigma V_{MN}} \quad (3.1)$$

Two specimens of tap water with slightly different conductivity were tested (Water$_1$ and Water$_2$). Their conductivities were measured with a liquid conductivity meter and are shown in Table 3.1.

Experimental methods were validated through finite element modeling using the electrical conductivity of the Water$_1$ specimen. Note that the value of the electrical conductivity inside the cell for numerical modeling can be arbitrary and is inconsequential to $K$. The corresponding measurement of $V_{MN}(V)$ is linearly dependent upon the electrical conductivity of the material inside the capsule (Ohm’s law). In other words, an increase in one will cause a decrease in the other and so will cancel each other for a constant value in $K$.

Table 3.1 shows strong agreement for both laboratory tests (specimens Water$_1$ and Water$_2$) yielding a value for $K$ of 0.056m and 0.055m, respectively. The computational modeling result shows a value for $K = 0.060$m, which is within 1% of the experimentally determined value. After the geometric factor of the capsule is identified, it may be filled with any material for evaluation of the material’s electrical conductivity.

The capsule (Figure 3.6) is filled with a nearly saturated sand ($S_e \approx 99\%$). It is difficult to fully saturate a material under atmospheric conditions without applying a backpressure to the specimen to ensure the voids are completely filled with water. Well-established triaxial cell procedures typically use backpressures to achieve saturation.

The electrical conductivity can be calculated using Equation 3.2 by measuring the conductance determined by the terrameter and using the geometric factor evaluated in the previous step:

$$\sigma = S/K \quad (3.2)$$
Two tests with different specimens were performed using a current injection of 10 mA. The results for each of the tests are shown in Table 3.2.

Table 3.1: Evaluated geometrical factor, \( K(m) \), for two experimental studies (Water\(_1\) and Water\(_2\)) and verification study through computational modeling (FE Model)

<table>
<thead>
<tr>
<th>Specimen</th>
<th>( \sigma ) (S/m)</th>
<th>I (A)</th>
<th>V (Volts)</th>
<th>( K(m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water(_1)</td>
<td>0.033</td>
<td>0.005</td>
<td>2.70</td>
<td>0.056</td>
</tr>
<tr>
<td>Water(_2)</td>
<td>0.034</td>
<td>0.005</td>
<td>2.64</td>
<td>0.055</td>
</tr>
<tr>
<td>FE Model</td>
<td>0.033</td>
<td>0.005</td>
<td>2.51</td>
<td>0.060</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>0.057</td>
</tr>
<tr>
<td>Std. Dev</td>
<td></td>
<td></td>
<td></td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 3.2: Evaluation of electrical conductivity, \( \sigma \) (S/m), for two specimens (A and B) with measured conductance and evaluated geometric factor

<table>
<thead>
<tr>
<th>Specimen</th>
<th>S (S)</th>
<th>( K(m) )</th>
<th>( \sigma ) (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.30E-04</td>
<td>0.06</td>
<td>0.011</td>
</tr>
<tr>
<td>2</td>
<td>6.50E-04</td>
<td>0.06</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Specimen 1 and 2 yielded an electrical conductivity of 1.1*10\(^{-2}\) and 1.2*10\(^{-2}\) S/m, respectively. The difference between the two tests is less than 10% and could be attributed to a small change in the saturation of the material, but is still reasonable experimental error. The electrical conductivity of the tap water from Table 3.1 showed slight variation from 3.3*10\(^{-2}\) S/m to 3.4*10\(^{-2}\) S/m in a matter of just an hour. Tap water is subject to variation in mineral concentration and temperature, both of which are a factor of electrical conductivity. Therefore, the variation in the electrical conductivity of the tap water introduced into the pore space of the sand could contribute to the experimental error observed. The average dry unit weight of both specimens is 17.3 kN/m\(^3\), which is less than 6% lower than the maximum measured dry unit weight observed from the tests performed on the prepared saturated sand in the tank given in Section 3.4.
3.3.2 Experimental Validation of Electrical Conductivity Using the Designed TBM Pipe Detection Tank

The second method for experimental testing of the electrical conductivity of the saturated sand uses the tank designed for the TBM pipe detection experiments (Figure 3.4) and employs a Wenner array (Figure 3.7) at the surface of the saturated sand filled tank (Figure 3.8). The sand is filled into the tank in five lifts. The procedure for lifts and saturation is presented in the tank preparation section (Section 3.4) of this chapter.

Figures 3.7(a) and 3.7(b) illustrate the dimensions and layout of the electrodes on a steel plate. The steel plate is used to simulate an electrically conductive cutterhead and was originally designed for use in another experiment not presented here. The four electrodes are equally spaced at 15.24cm apart defining a Wenner array with equal electrode spacing. The electrode array is centered on the face of the plate. Each of the four electrodes is made of a threaded A-13 steel plug that is electrically isolated from the plate by a plastic (G-11 Composite) bushing (Figures 3.7(c) and 3.7(d)). The electrode threads into the bushing and the bushing threads into the plate with nominal pipe threading to ensure a water tight fit (Figure 3.7(d)). If a water tight fit does not exist, then water may permeate between the electrode and the bushing to create an electrical short circuit from the electrode to the plate.

Once the tank is filled with saturated sand and the plate is assembled, the plate is lowered into the tank by means of a hydraulic arm (Figure 3.8(a)). The terrameter is connected to the four electrode array and a measurement can be made. Similar to the experimental measurement taken for the capsule, the geometric factor of the electrode array/plate/tank system is unknown and therefore the electrical conductivity cannot yet be determined. Again, computational modeling of this experiment is used to evaluate $K$. The model is shown in Figure 3.9.

Table 3.3 shows the resulting value of $K$ calculated from the model using a model material conductivity of $\sigma = 10^{-1}$ S/m. Using an evaluated $K$ of 17.8m, and a voltage measured
directly by the terramater of 50.8mV, an electrical conductivity of $\sigma = 1.1 \times 10^{-2} \text{ S/m}$ was calculated. Even though evaluated using a different experimental method, the electrical conductivity calculated by the experimental tank showed strong agreement to the conductivity determined using the capsule.

Figure 3.7: Four electrode Wenner array mounted on steel plate, (a) top view of plate and electrode dimensions, (b) side view of plate and electrode dimensions, (c) isometric view of threaded electrode and threaded plastic bushing (electrical insulator) not attached, (d) isometric view of threaded electrode and threaded plastic bushing attached

Figure 3.8: Experimental setup for evaluation of electrical conductivity, $\sigma \text{ (S/m)}$, of the saturated sand using the design pipe detection and a surface. Wenner electrode array connected to a steel plate, hydraulic arm lowering the plate onto the saturate sand surface (terrameter connected to the electrode array for measurement)
Figure 3.9: Isometric view of COMSOL finite element used to evaluate the geometric factor, $K(m)$, of the plate/sand/tank experiment

Table 3.3: Computational evaluation of the geometric factor, $K(m)$, to determine the electrical conductivity of the saturated sand within the tank

<table>
<thead>
<tr>
<th>Sample</th>
<th>V (mV)</th>
<th>K (m)</th>
<th>$\sigma$ (S/m)</th>
<th>n (stacks)</th>
<th>% std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.8</td>
<td>17.8</td>
<td>0.011</td>
<td>2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

3.4 Tank Preparation

The cylindrical tank is filled with the saturated sand and is compacted in five lifts (approximately 10-13cm in thickness each). This specific sand was identified as poorly graded sand (SP) with a $D_{50} = 0.81$ mm, and $C_u = 1.5$ [61].

First, the tank is filled with tap water to a height of approximately 10cm (Figure 3.10(a)). Sand is shoveled into the tank until a height of approximately 10-13cm (Figure 3.10(b)). After each lift, a vibratory probe is used to vibrate the sand in order to densify and further saturate the pore space by ensuring that little to zero bubbles are trapped between grains (Figure 3.10(c)). A picture of the vibratory probe can be seen in Figure 3.11. These probes are commonly used in construction processes for the densification of concrete and removal of air bubbles from the fluid concrete mixture. At each new lift, the tank is filled with more water to ensure that the height of
the sand does not rise above the height of the water (Figure 3.10(c)). This helps mitigate entrapment of air bubbles between grains as the sand is filled at each lift. This process is repeated until five lifts are completed and the tank is full of saturated sand (Figure 3.10(d)). While the use of a vibratory probe is commonly used in industry to densify and saturate the pore space for concrete compaction, it is not an accepted geotechnical standardized test for achieving consistent laboratory controlled soil properties.

For validation of consistent sand properties (namely unit weight) across TBM experiments, a series of samples were extracted from the top-most layer of saturated sand material in order to characterize and establish the ability to compact a uniform unit weight of the saturated sand inside of the tank. Multiple saturated sand tank preparations were performed (i.e., previous sand removed and refilled in accordance with the procedure and discussion from Figure 3.10, each with different lateral location of extracted samples (Figure 3.12).

To take the samples from each test, California Liner Samplers were used. Four California Samplers (one shown in Figure 3.13) were used with the dimensions shown in Table 3.4. All four of the samplers were pushed into the surface of the saturated sand for three different test configurations defined in Figure 3.12.

In test 1 (Figure 3.12(a)), the four samplers are inserted at 90 degree positions (12 o'clock, 3 o'clock, 6 o'clock and 9 o'clock) around the surface of the tank. All four of the samplers are placed 10.15cm on center, away from the center of the tank.

In test 2 (Figure 3.12(b)), the locations of the samplers are held the same as for test 1, but in this case, the model TBM is inserted in the middle of tank with help from the vibratory probe to identify if its presence impacts the unit weight of the material in the tank. This verification is important as the vibratory probe is also used to enable the TBM to be pushed into the dense sand material. Changes in the unit weight of the sand due to the presence of the TBM may impact the results of the experimental study and so it is important to verify this is not the case.
In test 3 (Figure 3.12(c)), the on-center locations of the samplers are increased from the center of the tank by 22.9cm to identify if any change in unit weight occurs as the radial distance from the center of the tank increases.

Figure 3.10: Illustration of the saturated sand tank filling process, (a) tap water poured into tank approximately 0.1m, (b) sand is lifted into the water for a height between 0.1 and 0.13m, (c) the sand is compacted and leveled using a vibratory concrete probe, (d) full tank of saturated sand.

Figure 3.11: Concrete vibratory probe used for in tank preparation for densification and saturation of sand.
Figure 3.12: Top view of three different sampling configurations.

Figure 3.13: Example of one California Liner Sampler
Table 3.4: Dimensions for four California Samplers used in dry unit weight tests

<table>
<thead>
<tr>
<th>California Sampler #</th>
<th>ID (cm)</th>
<th>Height (cm)</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.93</td>
<td>10.41</td>
<td>198.70</td>
</tr>
<tr>
<td>2</td>
<td>4.93</td>
<td>10.13</td>
<td>193.00</td>
</tr>
<tr>
<td>3</td>
<td>4.93</td>
<td>10.11</td>
<td>192.70</td>
</tr>
<tr>
<td>4</td>
<td>4.93</td>
<td>10.11</td>
<td>192.80</td>
</tr>
</tbody>
</table>

Figure 3.14 shows the progression of steps for the insertion and collection of the samplers in the tank for the test configuration shown in Figure 3.12(a). All four of the samplers are pushed into the saturated sand at the defined locations (Figure 3.14(a)). Each of the samplers are individually trenched into order to extract them (Figure 3.14(b)). In order to retain the material (water and sand) within the sampler, a plate is pushed underneath the sampler before it is fully extracted (Figure 3.14(c)). The sampler is placed in an oven tin, weighed, and is ready to be oven dried (Figure 3.14(d)).

Tables 3.5-3.7 show the results for the dry unit weight of each of the California Samplers for each of the test configurations from Figure 3.12. The dry unit weight tests results, shown in Tables 3.5-3.7, yield relatively consistent densities across the four samples and between configurations. The average densities observed are $18.0 \pm 0.19$, $17.7 \pm 0.28$, and $17.8 \pm 0.10$ kN/m³ for the test configuration Figure 3.12(a), 3.12(b), and 3.12(c), respectively.

Results demonstrate that the saturated sand can be compacted by vibratory probe and maintain a relatively consistent unit weight when the tank emptied and refilled. Bearce and Mooney [61] saw from experimental data of the identical sand that the effects of decreased conductivity through an increased density with depth was not observed in an electrical resistivity experiment using an identical tank of 1.32m in height for similar compaction method.
Figure 3.14: Method for dry unit weight test, (a) four samplers pushed into saturated sand, (b) trenched sampler, (c) sampler with retention plate underneath, (d) soil filled sampler in metal tin
Table 3.5: Evaluation of dry unit weight (kN/m$^3$) for each of four samplers (sampler configuration Figure 3.12(a))

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wet Soil (g)</th>
<th>Dry Soil (g)</th>
<th>Water (g)</th>
<th>Volume (cm$^3$)</th>
<th>Dry Unit Weight (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>433</td>
<td>370</td>
<td>63</td>
<td>198.70</td>
<td>18.3</td>
</tr>
<tr>
<td>2</td>
<td>412</td>
<td>350</td>
<td>62</td>
<td>193.00</td>
<td>17.8</td>
</tr>
<tr>
<td>3</td>
<td>415</td>
<td>353</td>
<td>62</td>
<td>192.70</td>
<td>18.0</td>
</tr>
<tr>
<td>4</td>
<td>415</td>
<td>353</td>
<td>62</td>
<td>192.80</td>
<td>18.0</td>
</tr>
<tr>
<td>Average</td>
<td>419</td>
<td>356</td>
<td>62</td>
<td>194.30</td>
<td>18.0</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>9.8</td>
<td>9.0</td>
<td>0.8</td>
<td>2.94</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 3.6: Evaluation of dry unit weight (kN/m$^3$) for each of four samplers (sampler configuration Figure 3.12(b))

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wet Soil (g)</th>
<th>Dry Soil (g)</th>
<th>Water (g)</th>
<th>Volume (cm$^3$)</th>
<th>Dry Unit Weight (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>431</td>
<td>366</td>
<td>64</td>
<td>198.70</td>
<td>18.1</td>
</tr>
<tr>
<td>2</td>
<td>404</td>
<td>342</td>
<td>62</td>
<td>193.00</td>
<td>17.4</td>
</tr>
<tr>
<td>3</td>
<td>410</td>
<td>348</td>
<td>62</td>
<td>192.70</td>
<td>17.7</td>
</tr>
<tr>
<td>4</td>
<td>411</td>
<td>349</td>
<td>62</td>
<td>192.80</td>
<td>17.8</td>
</tr>
<tr>
<td>Average</td>
<td>414</td>
<td>351</td>
<td>62</td>
<td>194.30</td>
<td>17.7</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>11.6</td>
<td>10.3</td>
<td>1.4</td>
<td>2.94</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 3.7: Evaluation of dry unit weight (kN/m$^3$) for each of four samplers (sampler configuration Figure 2.12(c))

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Wet Soil (g)</th>
<th>Dry Soil (g)</th>
<th>Water (g)</th>
<th>Volume (cm$^3$)</th>
<th>Dry Unit Weight (kN/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>422</td>
<td>361</td>
<td>61</td>
<td>198.70</td>
<td>17.8</td>
</tr>
<tr>
<td>2</td>
<td>413</td>
<td>351</td>
<td>62</td>
<td>193.00</td>
<td>17.8</td>
</tr>
<tr>
<td>3</td>
<td>413</td>
<td>349</td>
<td>64</td>
<td>192.70</td>
<td>17.8</td>
</tr>
<tr>
<td>4</td>
<td>416</td>
<td>354</td>
<td>63</td>
<td>192.80</td>
<td>18.0</td>
</tr>
<tr>
<td>Average</td>
<td>416</td>
<td>353</td>
<td>63</td>
<td>194.30</td>
<td>17.8</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>4.4</td>
<td>5.3</td>
<td>1.2</td>
<td>2.94</td>
<td>0.10</td>
</tr>
</tbody>
</table>
3.5 Experimental Method

This experimental study uses the designed tank and scaled TBM (Section 2.2) to experimentally analyze the ability for electrical resistivity integrated on a TBM to predict a metallic pipe/rod ahead of the tunnel face. The various electrodes on the scaled TBM are used to evaluate two unique electrode arrays called integral mode and scan (Figure 3.15). Figure 3.15 shows the face of the cutterhead and the differences between the two electrode configurations.

In integral mode, the entire TBM is used as the current source electrode (A). The remaining Ag/Ag-Cl disks represent cutting tools and measure nine independent locations (M₁ through M₉) of electrical potential. In scan mode, the center Ag/Ag-Cl disk electrode is used to inject current. The remaining eight (M₁ through M₈) disk electrodes are used to measure electrical potential. In both cases, the ring electrodes are used as the current sink (B) and potential measurement (N) consistent with Figure 3.1.

At each value of \( z_D \), a measurement of voltage is taken for each combination of M and N. The terrameter does not directly measurement electrical noise (i.e., a passive voltage measurement without current injection). For a single combination of M and N, measurements of \( V(V) \) are taken by the terrameter until a maximum predetermined standard deviation can be achieved between measurements of voltage (called stacks). For all experimental measurements, the standard deviation limit is set to \( \leq 2\% \) and was always achieved with only two stacks for these experiments.

The terms integral mode and scan mode refer to the nature of the electrical current injection and were adopted from similar approaches used in the field by commercially available systems [1]. The reader should note that the terms scan and integral mode do not imply that these configuration are replications of the BEAM system configurations. Here they are used to generally convey the sentiment of BEAM and are still technically different. These configurations do not imply that they use any current focusing because the experimental scale model TBM
does electrically isolate the cutterhead from the shield. Furthermore, the experiments in this study do not consider IP methods and only use DCR with direct current injection.

Since integral mode injects through the entire TBM, the idea is that the cutterhead and shield distribute the electrical current equally and so any difference/s ahead of the TBM will attract/repulse current across the entire face. This method was hypothesized to be more of an averaging approach in the field. In contrast, scan mode injects from a single cutting tool and so provides a much smaller volume of which current is injected. As the cutterhead rotates relative to tunnel longitudinal axis, the cutting tool will rotate about the tunnel longitudinal axis and ‘scan’ the ground for smaller finite anomalies.

The research performed in this chapter and subsequent chapters will show that the ability to detect small anomalies (e.g., boulder, pipe, sand lens) and image their lateral location on the tunnel face is not solely dependent upon the type of electrical current injection (TBM or cutting tools) and relies on a balance between the position of current source/sink as well as the potential measuring electrodes.

Figure 3.16 illustrates the laboratory model set up and dimensions with the scaled TBM in the plastic tank. The TBM is positioned vertically (z-axis) in the tank and excavates toward the metal pipe/rod at a distance of $z_D$ (cm) away from the TBM. The orientation is inconsequential to the results as electrical flow is not affected by gravitational force. A total current magnitude of 10mA is used for current injection/retrieval for the remainder of this experimental study. This level of current injection is arbitrary. Any percent increase or decrease in the level of current injection in the low electrical noise environment will only scale the measured voltage by the same percentage.

Figure 3.17 shows photographs of the experimental set up with an angled top view (Figure 3.17a), side view (Figure 3.17b) and a demonstration of the scaled TBM being pushed in the saturated sand to simulate the excavation process (Figure 3.17c). The TBM is incrementally lowered from near the surface of the soil toward the metallic pipe/rod. Figure 3.18
shows a series of illustrations that show how the TBM advances toward the pipe/rod for decreasing values of $z_D$(cm). At discrete values of $z_D$(cm), a measurement of $V_{MN}(V)$ is taken for each pair of potential electrodes (e.g., $M_1N$, $M_2N$, $M_3N$….etc.). For integral mode, this consists of nine measurements at each location of $z_D$. For scan mode, this consists of eight measurements at each location of $z_D$.

Figure 3.15: Two electrode configurations (N and B not shown) used for experimental analysis called (a) integral mode and (B) scan mode
Figure 3.16: Dimensions of laboratory scaled setup of tunnel boring machine (TBM) advancement toward a metallic pipe ($\sigma = 10^6 \text{ S/m}$) located in saturated sand ($\sigma \approx 10^{-2} \text{ S/m}$)

The collected voltage data demonstrated only small differences in $V_{Mn,N}(V)$ across all electrode pairs for a single value of $z_D$. Curves of $\Delta V$ vs. $z_D$ for all electrode pairs (nine for integral mode and eight for scan mode) nearly overlaid one another when plotted. An average measurement in $V_{MN}$ for all electrode pairs at a single value of $z_D$ is averaged as given by:

$$V_{AVG} = \left( \frac{\Sigma^n V_{M1,N} + V_{M2,N} + V_{M3,N} \ldots + V_{MN,N}}{n} \right)$$

(3.3)

where $V_{M1,N}$, for example, is the voltage measured between electrode pair $M_1$, $N$ and $n$ is the number of electrode pairs used in the average ($n = 9$ for integral mode, $n = 8$ for scan mode).

Due to the symmetry of the experimental procedure, an averaging of the data is not expected to contribute to any conclusions drawn between the comparison of data sets.
Figure 3.17: Photos of laboratory experiment for electrical resistivity applied to TBM for prediction of metal pipe ahead of TBM. (a) top view saturated sand in tank, (b) side view of ribbed plastic tank, (c) scaled model TBM being inserted into saturated sand.

Figure 3.18: Progression of the TBM toward the metallic rod/pipe for decreasing values of $z_D$. 
3.6 Results and Analysis

Laboratory experiments were performed using the scaled TBM and the tank designed in Section 2 of this chapter. The experiments tested the ability for the two electrode arrays (integral and scan mode) to detect a metallic pipe or a metallic rod that has been placed in a tank full of saturated sand. The homogeneous condition (i.e., no pipe) was not experimentally tested here, but was computationally modeled in Section 2 of this chapter for $H_{TBM}$.

Figure 3.19 shows the experimental results for $\Delta V_{AVG}(mV)$ vs. $z_D(cm)$ for both integral mode and scan mode electrode configurations as the TBM approaches a hollow metal pipe ($OD = 1.3cm$, $ID = 1.0cm$). Chapter 2 presented $\Delta V$ for a surface-based electrical resistivity array where the current measurement of $V$ was referenced to $V_{FAR-FIELD}$. $\Delta V$ presented here is analogous to the discussion given in Chapter 2.

Figure 3.19 shows that as $z_D$ decreases (i.e., the TBM moves toward the metallic pipe) that $\Delta V_{AVG}$ becomes increasingly negative. This is consistent with the analysis shown in Chapter 2 for a relatively conductive planar difference approaching a surface electrode array. In this case, it can be inferred that the far field condition was achieved for measurements values of $z_D \geq 19cm$, and the pipe has been detected somewhere between $16.5cm \leq z_D \leq 19cm$. These results show that some difference ahead of the TBM is detected over $18cm$ (nearly 3 TBM diameters) before it is physically encountered. In comparing the two electrode arrays, the plots in Figure 3.19 for integral mode and scan mode show very little differences in $\Delta V_{AVG}$. Chapter 4 will analyze how some modifications to this configuration of integral and scan mode can drastically separate the two arrays in terms of their ability to detect incoming differences ahead of the TBM.

Even though the pipe has been sensed nearly three TBM diameters away from the tunnel face, these results are not conclusive to the unique presence of a metallic pipe, its size, and lateral orientation on the tunnel face (i.e., centered or off-centered). As a means of ‘imaging’ the size
and/or lateral location of the pipe, the following contour plots show contours $\Delta V$ within the space between electrodes on the face of the TBM for integral mode and scan mode.

Contour plots of voltage (measurement of $\Psi$ at $M(V)$ at the face referenced to $\Psi$ at $N(V)$ back along the tunnel lining) show an interpolated distribution of voltages and provide insight, if any, as to the lateral location and size of the pipe ahead of the TBM. The contour plots are shown in the following figures.

![Contour plots of voltage](image)

**Figure 3.19:** Measured average electrical potential, $\Delta V_{AVG}(mV)$ for laboratory scaled TBM model advancing toward (decreasing values of $z_D(cm)$) hollow metal pipe (OD = 1.3cm, ID = 1cm) in saturated sand ($\sigma \approx 10^{-2}$ S/m)

The contour plots in Figures 3.20 and 3.21 show cross sections of $\Delta V$(mV) measured at the tunnel face (i.e., where the cutting tools make contact with the virgin earth) for various values of $z_D$ away from the metal pipe. Figure 3.20(a) and Figure 3.21(a) show a cross section that is overlain with a to-scale TBM, electrodes and metal pipe. It should be noted that the scales of $\Delta V$ on each of the contour plots are different and are intentionally plotted this way. Since $\Delta V$ continues to decrease as the TBM advances toward the metal pipe, it is unrealistic to
assign a scale that can capture the maximum and minimum changes seen across all contour plots. Regardless, the results in the contour plots are generally inclusive and unfortunately do not resemble the shape and/or orientation of the metal pipe even for low values of $z_D$.

This is with one exception in integral mode where the $z_D = 4.6$ cm (about $\frac{3}{4}$ of a TBM diameter). In this case, a vertically oriented concentration in $\Delta V$ can be observed that is negative with respect to the sides of the contour plot. This still does not conclude that a pipe is present, however, the negative change in electrical potential toward the center of the tunnel face indicates a relatively conductive body when compared to the surrounding earth. The look of this contour is similar to what can be seen in computational modeling contour plots and will be shown in Chapter 5 for the detection of a pipe ahead of a TBM. In scan mode, the results are inconclusive toward the shape/size or orientation of any change in front of the TBM. This result is due to a lack of information in the center of the cutterhead. Since the current injection was performed with the centermost electrode on the cutterhead, it cannot also be used to measure electrical potential (contrary to BEAM and BEAM suggestions).

This laboratory experiment suggests that electrical resistivity may be capable of identifying a conductive body ahead of the TBM. However, the orientation, size and position of the pipe is inconclusive. Yet, contour plots only offer a primitive alternative to ‘image’ the space in front of the TBM. Inversion is a field of recent research activity and may achieve more insight into the spatial distribution of material ahead of the TBM based upon the measurements in potential at the tunnel face.

A second experiment was conducted using a solid metal rod to determine if a solid rod (opposed to a hollow pipe) of the same diameter is detected differently in integral mode. Scan mode was not studied here as it provided very similar results in $\Delta V$ vs. $z_D$ and the resulting contour cross sections did not provide any conclusive information due to low resolution of data. The tank was emptied completely and refilled in accordance with the tank preparation procedure.
detailed above. The solid rod was placed at approximately 20cm from the bottom of the tank, identical to the pipe experiment.

Figure 3.22 compares plots of $\Delta V_{AVG}$ vs. $z_D$ for a solid rod and a hollow metal pipe of equal OD = 1.3cm (integral mode only). In both cases, $\Delta V_{AVG}$ continues to decrease, again suggesting that a conductive difference is present in front of the TBM. Again, it can be interfered that the pipe has been detected for $16.5\text{cm} \leq z_D \leq 19\text{cm}$. When compared to the experimental data shown for the rod, the look-ahead distance is achieved when $z_D$ is between 14cm and 16cm. However, it is important to note that due to the geometry of the experimental setup (i.e., the location of the ring sink electrode from the front of the TBM), that greater distances of $z_D$ could not be made. Still, given the data in Figure 3.22, further data may not be necessary given small initial decreases in $\Delta V_{AVG}$ at larger values of $z_D$. For example, in the pipe experimental, $\Delta V_{AVG}$ decreases only by 20mV across a $z_D$ span of 2.5cm (i.e., 19 to 16.5cm).

Computational modeling shows that a solid rod has no additional influence beyond a hollow pipe of similar outer diameter; the measured potential is identical. However, the experimental results were found to be different. The most significant difference between the experimental results is the shape of the response as the TBM approaches. The hollow pipe elicits a subtly increasing $\Delta V_{AVG}$ as $zD$ decreases, until $zD=6\text{cm}$, whereafter, $\Delta V_{AVG}$ increases in magnitude dramatically. The solid rod elicits a much different response, with $\Delta V_{AVG}$ increasing more uniformly as the TBM approaches.

A likely source of error could arise from differences in the experimental setup between the pipe test and rod test (i.e., non-standardized compaction method provided inconsistent density). Another source of error could result from the fluctuation in pore fluid conductivity over time. Tap water was used to saturate the sand. Since tap water does not maintain its conductivity over time (temperature, salinity, mineral content) it is possible that its conductivity will have changed slightly between tests.
The contour plots in Figure 3.23 are shown for cross sections of the tunnel face as the TBM advances toward the solid metal rod using integral mode. Similar to the previous contour plots, Figure 3.23(a) shows an overlain, to-scale TBM, electrodes and metal rod for scale reference.

When compared to the contours (both scan and integral mode) from the hollow pipe simulations, the contours for the solid rod are somewhat more consistent in the ability to image the metal rod. At cross sections of \( z_D = 9.6 \text{cm}, 6.3 \text{cm}, \) and \( 3.3 \text{cm} \), it is possible to observe a slightly rotated length of concentrated \( \Delta V \) that is more negative than its surroundings. Even though this result is still not 100% conclusive for the ability to uniquely image the rod, these findings do suggest a stronger ability to resolve the solid rod than for the hollow pipe.

### 3.7 Finite Element Model vs. Experimental Model

The experimental results show the integrated electrode array is able to detect the pipe and rod before it is encountered by the TBM, but that the nature and shape of the \( \Delta V_{AVG} \) vs. \( z_D \) response are quite different between the rod and pipe. In this section, the experimental data, presented previously, is compared to 1:1 scale computational model of the experimental study.

The experimental setup was modeled using COMSOL Multiphysics. The model space can be seen in Figure 3.24. The meshing parameters, boundary conditions and material properties are identical to those presented earlier in this chapter for the analysis of tank boundary conditions \( H_{TANK} \) and \( R_{TANK} \). The exception is the saturated sand, which was given an assumed \( \sigma = 0.011 \text{ S/m} \) measured by experimental procedures earlier in the chapter. An important note about the conductivity of the sand is that this initial model defines an electrical conductivity that is uniform with depth in the tank. The results that will be shown in the following plots do not support this assumption and so further modeling suggests a conductivity of the sand that spatially varies with depth.
Figure 3.20: Integral mode cross sections $x$(cm) vs. $y$(cm) ($z = 1$mm) of electrical potential, $\Delta V$(mV) for laboratory scaled TBM model advancing toward hollow metal pipe in saturated sand. (a) $z_D = 16.5$cm, (b) $z_D = 14.7$cm, (c) $z_D = 11.4$cm, (d) $z_D = 5.8$cm, (e) $z_D = 4.6$cm
Figure 3.21: Scan mode cross sections $x$(cm) vs. $y$(cm) ($z = 1\text{mm}$) of electrical potential, $\Delta V$(mV) for laboratory scaled TBM model advancing toward hollow metal pipe in saturated sand. (a) $z_D = 16.5\text{cm}$, (b) $z_D = 14.7\text{cm}$, (c) $z_D = 11.4\text{cm}$, (d) $z_D = 5.8\text{cm}$, (e) $z_D = 4.6\text{cm}$
Figure 3.22: Measured average electrical potential, \( \Delta V_{AVG}(mV) \) for laboratory scaled TBM advancing toward (decreasing values of \( z_D \)(cm)) either a solid metal rod (OD = 1.3cm) or a hollow metal pipe (OD = 1.3cm, ID = 1.0cm) in saturated sand (\( \sigma \approx 10^{-2} \) S/m)

Figure 3.25 shows a comparison of the experimental model results with the computational results for the integral mode configuration advancing towards the metallic pipe. While the curves yield similar decreasing \( \Delta V_{AVG} \) for decreasing values of \( z_D \), their shapes do not align well suggesting the one or more model assumptions may be inaccurate. The general double curvature of the experimental results is captured in the computational model response. However, the FE results reveal the pipe is first observed approximately 2 cm prior to the experimental results and that the magnitude of \( \Delta V_{AVG} \) grows much greater with \( z_D \) than that measured experimentally (this may be explained by experimental electrical noise, which can limit the ability to detect incoming differences). Specifically, within the first 3 cm of observation, the FE model \( \Delta V_{AVG} \) has grown to more than five times greater than the experimental \( \Delta V_{AVG} \). The FE results capture the nature of the second curve (at \( z_D = 5 \)cm) but show it to be more gradual than that observed experimentally.
Figure 3.23: Cross sections $x$(cm) vs. $y$(cm) ($z = 0$) of electrical potential, $\Delta V$(mV) for laboratory scaled TBM model advancing toward metal rod in saturated sand ($\sigma = 10^{-2}$ S/m). (a) $z_D = 17.8$cm, (b) $z_D = 12.7$cm, (c) $z_D = 9.6$cm, (d) $z_D = 6.3$cm, (e) $z_D = 3.3$cm
The reader should note that the recorded values of \( z_D \) for the experimental study are not identical to those evaluated in the computational model. For example, the experimental data is stopped at a \( z_D \approx 4 \text{cm} \), but the computational model extends to \( z_D \approx 1 \text{cm} \). The reason for this is due to the ability to control the advancement of the TBM toward the pipe. In the laboratory, the TBM is difficult to advance, particularly at greater depths. In the finite element model, it is possible to get very close to the pipe/rod since the TBM is controlled by a computer code.

The comparison of the experimental results to the finite element result in Figure 3.25 shows that the initial detection of the pipe is clearly defined at different locations. The finite element model suggests that pipe is detected easily over \( z_D \) greater than 20cm by an initial \( \Delta V_{\text{AVG}} \) drop of nearly 200mV between 20.5cm and 17cm. In contrast, the experimental results show relatively slight decreases in \( \Delta V_{\text{AVG}} \), yielding a decreases of only 20mV between a larger span of \( z_D \) of 18.5cm to 11.5cm. The disagreement of this initial look-ahead distance and the shape of the curves may be addressed through questioning the original assumption where the saturated sand is expected to have uniform electrical conductivity with depth. The analysis and discussion of this will be performed at the end of this section.
Figure 3.25: Comparison of experimental and computational model results as the TBM advances towards a hollow metal pipe (OD = 1.3cm, ID = 1.0cm) in saturated sand (σ = 0.011 S/m, constant with depth)

Figure 3.26 shows a comparison of the experimental model results with the computational results for the integral mode configuration advancing towards the metallic rod. The FE results of the solid rod are practically identical to the pipe (discussed below), exhibiting the double curvature response. The experimental pipe results exhibit a much more gradual response, both when the rod is first observed and when the rod is close (zD < 5 cm).

In Figure 3.27, curves of $\Delta V_{\text{avg}}$ vs. $z_D$ from the finite element modeling results are plotted to show a comparison between the expected response for the pipe and rod when the experiment performed with uniform sand conductivity, $\sigma = 0.011$ S/m. The results show that the solid rod (vs. hollow pipe) does not significantly affect the prediction ability ahead of the face. This suggests that the pipe is already so electrically conductive that by adding more conductive volume within its boundaries does not alter the flow of electrical current significantly. In the previous section, contrasts in the experimental curves between the pipe and the rod were attributed to the volumetric conductivity differences (i.e., rod has more metal volume than the

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pipe). However, the FE analysis denies this original theory in favor of another contrast between the experiments. The discrepancies in the experimental results between pipe and rod could be attributed to poor compaction procedures although a verification of standardized compaction was attempted previously in this chapter. Due to the similarity in the model results, the dissimilarity in the experimental results may suggest that the compaction procedure did not yield consistent conductivity results between tests, particularly its capacity to vary spatially within the tank. The following analysis and discussion will address this.

![Diagram](image)

**Figure 3.26: Comparison of experimental and computational model results as the TBM advances towards a hollow metal pipe (OD = 1.3cm, ID = 1.0cm) in saturated sand (σ = 0.011 S/m, constant with depth)**

There exists a possibility that the electrical conductivity of the sand in the tank may fluctuate spatially, and may decrease with depth due to overburden-induced compaction. To explore this, additional computational models were run where the electrical conductivity of the sand was varied above and below the expected conductivity of σ = 0.011 S/m, where each
model is given a uniform conductivity. By plotting the model results next to one another, it is possible to gather a sensitivity of the model to fluctuation in uniform sand conductivity.

![Figure 3.27: Comparison of computational model results (pipe vs. rod) in saturated sand (σ = 0.011 S/m, constant with depth)](image)

A parametric analysis was performed to determine the sensitivity of $\Delta V_{AVG}$ to the electrical conductivity of the sand. Figure 3.28 shows computational results of various constant $\sigma$ models compared with the experimental pipe results. Figure 3.28 shows that some aspects of the modeled response are very sensitive to $\sigma$, namely the degrees of double curvature and the slope of the $\Delta V_{AVG}$ vs. $z_D$ between the curves. The FE model results show that the theoretical look-ahead distance is not influenced by $\sigma$, i.e., non-zero $\Delta V_{AVG}$ begins at $z_D = 21$ cm. However, given that the experimental response is subject to noise, it is evident that look ahead distance would be under-reported experimentally for higher $\sigma$. The location of the inflection point for the second curve (around $z_D = 5$ cm) is not influenced by $\sigma$; however, the slope of $\Delta V_{AVG}$ is strongly influence by $\sigma$. 

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A comparison of the experimental and computational pipe results suggests that the electrical conductivity is decreasing with depth, particularly in the vicinity approaching the pipe. This is evident by observing how the experimental curve trends towards the FE results of increasing $\sigma$ as $z_D$ decreases. The experimental results match the FE results with $\sigma = 0.1$ S/m when the pipe is first detected and over the range $z_D > 10$ cm. In the region $z_D = 5 - 10$ cm, the results suggest that $\sigma$ is decreasing. Note that the FE analysis is performed with $\sigma$ spatially constant throughout the model; however, the $\sigma$ between the TBM and pipe would largely control the FE results, and therefore it is reasonable to use constant $\sigma$ model results to explain the experimental results. This decrease in $\sigma$ could be due to densification with depth. The sharp increase in $\Delta V_{AVG}$ from $z_D = 6$ cm to 4 cm suggests that $\sigma$ has dramatically decreased (on the order of 0.005 S/m towards the bottom of the tank, however, the values of $\sigma$ modeled here are still within a reasonable range for the conductivity of the sand.

A comparison of uniform conductivity models to the experimental results for the rod are shown in Figure 3.29. Again, the results suggest that the original assumption of uniform $\sigma$ for the saturated sand is likely inaccurate. When the sand is given $\sigma = 0.1$ S/m, larger values of $z_D$ agree well ($z_D > 12.5$cm), but after the experimental results gradually increase while the computation results display the double curvature trend, described above. For lesser values of $z_D$ a decrease in conductivity could explain the discrepancies between the uniform computational model and the likely anisotropic model. Due to the differences in the experimental data (pipe vs. rod) it is expected the spatial distribution in conductivity of the saturated sand is different for the pipe experiment compared to the rod experiment. This is attributed to inconsistent compaction between experiments.
Figure 3.28: Comparison of experimental and computational model for measured average voltage, $\Delta V_{\text{AVG}}$ (mV) vs. $z_D$ (cm) as the TBM advances towards a hollow metal pipe (OD = 1.3cm, ID = 1.0cm) for various values of uniform $\sigma$ (S/m).

It is not certain how the conductivity is graded with depth (e.g., linear, quadratic), but it is clear that the experimental sand conductivity is not uniform. The analysis performed in Figures 3.28 and 3.29 demonstrate that an analytical model that varies in conductivity between 0.1 S/m and 0.005 S/m may provide fitting for the experimental pipe and rod experiments. In order to fully characterize the distribution of conductivity within the tank, a process called inversion is necessary but is not discussed here and is listed as a limitation of the research presented in this dissertation.
Figure 3.29: Comparison of experimental and computational model for measured average voltage, $\Delta V_{\text{AVG}}$ (mV) vs. $z_D$ (cm) as the TBM advances towards a solid metal rod (OD = 1.3cm) for various values of uniform $\sigma$ (S/m)

3.8 Conclusions

An experimental study was performed using a scaled TBM model with integrated electrical resistivity electrodes. Two unique electrode configurations were used and made several spatial measurements of voltage at the tunnel face as the TBM advanced toward a metallic pipe or rod of known size and location in a tank full of saturated sand. The experimental results were also compared to finite element models (1:1 scale), which reproduced the experimental setup in order to validate the computational models for further full-scale finite element analysis.

The following conclusions can be drawn from the results presented in this chapter:
• For the detection of a pipe that is laterally centered in the tunnel face, integral mode and scan mode provide nearly identical ability to detect the pipe when electrical current is injected symmetrically (either full TBM or centered on the cutterhead through a cutting tool).

• Either integral mode or scan mode are capable of identifying a conductive difference ahead of the TBM by almost three TBM diameters.

• The ability to unique identify the presence of a pipe or rod is not conclusive, however, the data suggests that, in comparison of these two configurations, integral mode was able to resolve a relatively narrow conductive difference that was centered in the tunnel face within 1.5 TBM diameters.

• When the experimental data was compared to the finite element results, both show that the electrode array has predicted an incoming conductive difference ahead of the TBM. However, the computational results do show correlate strongly with experimental curves with respect to general shape, particularly how computational models do not reproduce ideal, smooth exponential curves.

• By assuming an inaccurate experimental evaluation of the conductivity for the saturated sand within the tank of $\sigma = 0.011 \, \text{S/m}$, further computational modeling shows that perhaps the experimental compaction procedure does not uniformly densify the saturated sand versus depth. An increase in sand density with depth could explain a gradient in electrical conductivity and therefore more closely resemble experimental conductions. In order to conform the computational results to the experimental results better, a solution the spatial variation in sand conductivity is necessary, but is expected to rest within $0.005 \, \text{S/m} \leq \sigma \leq 0.1 \, \text{S/m}$.

These experimental simulations do not suggest that integral mode is better than scan mode for the detection of the metallic pipe/rod. In these experiments, the spatial resolution of
data is extremely lacking with only eight or nine points of information throughout the entire tunnel face. In the field, it is highly recommended that for the detection of smaller anomalies in the face, dozens of electrodes should be employed on the cutterhead to increase the spatial resolution of data.
CHAPTER 4

INFLUENCE OF THE INTERFACE REGION AROUND TBM ON ELECTRICAL RESISTIVITY IMAGING

4.1 Introduction

This chapter presents a computational finite element study that investigates the influence of the so-called interface region on various electrical resistivity arrays to predict an incoming vertical planar difference in geology. The interface region is modeled as a volume of material that surrounds the exterior of the TBM body and interfaces with the virgin earth. This volume of material is not well understood and so this study will evaluate its influence across a wide range of possibilities in order to understand its electrical influence, if any.

Depending upon the type of material expected along the tunnel alignment, tunnel excavations can be carried out by a wide range of TBM types such as pressurized face TBMs (slurry shield and earth pressure balance (EPB)) used in soft ground conditions to ensure face stability and non-pressurized or open-mode TBMs used in more competent hard rock tunnels with low risk of water inflows.

The influence of the interface region is evaluated at three separate conductivity values. Each of the three conductivity values represents a TBM type. For example, a slurry shield injects a bentonite slurry to mix with excavated muck, whereas EPB injects a foam mixture of surfactant and air to mix with the soil and create a toothpaste-like material. It is expected that the electrical conductivity of these materials will be significantly different from one another and are modeled accordingly in the computational studies: $10^{-15}$ S/m (hard rock TBM), $10^{-6}$ S/m (EPB TBM), $10^0$ S/m (slurry TBM). Six unique electrode configurations are considered to determine how each configuration is influenced under different interface regions conditions of both geometry and material properties (or associated TBM type).
4.2 The TBM Tunneling Environment and the Interface Region

The TBM tunneling environment can be modeled as a hollow cylinder of diameter $D$ located at a cover depth of $C$ below the earth’s surface (Figure 4.1(a)). The TBM structure is located at the closed end (right-hand side in Figure 4.1) of the cylinder and is comprised of both the cutterhead and the shield. To the left of the TBM structure is a lining constructed of either shotcrete, cast-in-place concrete or precast concrete segments. Unlined tunnels are not considered here, but are of no consequence to the findings in this chapter. The inside of the tunnel is comprised of air at atmospheric pressure. Figure 4.1(a) shows a simplified tunneling environment where the TBM makes perfect physical contact with the surrounding formation. In reality, there may exist some complexities regarding the perfect contact case shown in Figure 4.1(a) and may be generated by the introduction of cutting tools shown in Figures 4.1(b) and 4.1(c).

In tunnels where a precast lining is used, such as soft ground and unstable hard rock conditions, the TBM uses angled cutting tools (Figure 4.1(b)) on the outer radius of the cutterhead to over-excavate and create an annulus around the shield that extends from the cutterhead to the back of the TBM shield. The material in the annulus depends highly upon the TBM type and will be discussed later in this section. Once the precast lining is constructed behind the TBM, the annulus between the outside (extrados) of the lining and the excavated opening is filled with a pressurized grout.

An interface region exists between the TBM and the formation, created by a combination of a) a mixing action from the cutting tools in front of the TBM cutterhead and b) an over-excavated annulus created from cutting tools on the outer radius of the TBM cutterhead. The dimensions and material properties of the interface region are quite variable and may depend on TBM type, cutting tool size and geometry, overburden pressure, ground type and additives injected during excavation.
Figure 4.1: TBM environment geometry and material definitions, (a) isometric simplified TBM, (b) side-view TBM with cutting tools, (c) isometric TBM with cutting tools

Cutting tools include scrapers, rippers and/or disc cutters, each with a range of sizes. In general, cutting tool size can be on the order of $10 - 40\text{cm}$ (e.g., [62], [63]) and is specified based upon the diameter of the TBM, TBM type, and the ground conditions (soil type and overburden pressure). This analysis will assume large cutting tools with a size of 40 cm in order to determine their maximum influence. Since the annulus is formed by means of angled cutting tools, the analysis will assume a reasonable annulus thickness of 15 cm. This annulus
dimension is less than the dimension of the cutting tools themselves (due to their angled position) and is on the larger size as estimated by previous excavation practice (references). This study investigates the influence of the larger cutting tool size (i.e. larger interface region) because it aims to investigate the maximum influence of the interface region. For small cutting tools, the influence of the interface region would yield similar results but with less influence.

The electrical conductivity of the interface region could yield different values across TBM types and ground conditions. For hard rock tunneling, the region may be approximated as a volume of air with pieces of crushed and broken rock. The air phase will dominate in this case. For soft ground pressurized face tunneling, TBMs typically excavate using soil conditioning agents or water (earth pressure balance, EPB), or bentonite slurry (slurry TBM). To reflect these conditions, this study considers three values for the interface region conductivity based upon TBM type: \(10^{-15}\) S/m (hard rock TBM), \(10^{-6}\) S/m (EPB TBM), \(10^{0}\) S/m (slurry TBM). The interface region is divided into a disk and annulus as illustrated in Figure 4.1. The disk is approximated as a cylinder of thickness \(t_D = 40\text{cm}\) (equal to the size of the cutting tool), and the diameter of the TBM, \(D = 10\text{m}\). The disk is assigned an electrical conductivity, \(\sigma_D\). The annulus is approximated as a tube given an inner diameter equal to the TBM diameter, and an outer diameter equal to the TBM diameter plus 30cm. The annulus extends from the front of TBM cutterhead, back to the end of the TBM shield. The annulus is given an electrical conductivity \(\sigma_A\). The reader is encouraged to review Appendix A, which gives an overview of the TBM and how different types of TBMs operate.

Figure 4.2 shows four geometrical configurations of the interface region. Each of the configurations exists under the conditions shown adjacent to each configuration. Under highly complex conditions, it is possible where \(\sigma_D \neq \sigma_A\) but this analysis will not consider these rare cases and always define that \(\sigma_D = \sigma_A\).
Figure 4.2: Four assumptions for the configurations for the interface region, (a) no region (b) disk and annulus (c) disk only (d) annulus only

- **Theoretical model (interface region is not considered)**
- **TBM and surrounding virgin earth have perfect physical contact**
- **Could closely follow very soft ground conditions (soft clay) with no injected additives to aid excavation process**

(a)

- **Prediction for full existence of the interface region**
- **TBM and surrounding virgin earth have no physical contact and are separated by the interface region**
- **Present in both hard rock and soft ground conditions**
- **Cutting tools rip/scrape virgin earth in front of cutterhead to create the disk**
- **Cutting tools around perimeter of cutterhead, over-excavate an annulus**

(b)

- **Prediction for partial existence of the interface region (disk only)**
- **TBM and surrounding virgin earth have partial physical contact, and are separated only by the disk**
- **Cutting tools rip/scrape virgin earth in front of cutterhead**
- **Annulus is non-existent or insignificant:**
  - Perimeter cutting tools dulled, no longer provide sufficient excavation for annulus
  - Earth converges around shield, annulus becomes insignificant

(c)

- **Prediction for partial existence of the interface region (annulus only)**
- **TBM and surrounding virgin earth have partial physical contact, and are separated only by the annulus**
- **Perimeter cutting tools over excavate an annulus**
- **Soft Ground Conditions:**
  - Slurry/conditioner ports in cutterhead suddenly fail to inject in front of TBM, but previous additives still exist in annulus
- **Hard Rock Conditions:**
  - Cutting tools have dulled/shortened; cutterhead scrapes tunnel face.
4.3 Electrode Configurations and Ground Conditions

Figure 4.3 presents the six electrode configurations examined in the computational modeling. Each illustration gives a qualitative representation of current flow lines. The flow lines move from the current source electrode (A) to the current sink electrode (B) much like those presented in Chapter 1 for surface-based and borehole-based methods. Lines of equipotential are not shown here due to spatial constraints in the figure. Each of these electrode configurations will be analyzed for various assumptions of the interface region from Figure 4.2 (geometry and material property). The evaluation of each of the electrode arrays will be carried out by comparing observed current densities and measured potential sensitivity. A total current of 15 A is injected into the formation and is based upon analysis performed in Chapter 2 (also published in Schaeffer [64]) for safe levels of current injection/retrieval. This value is theoretical; a case by case analysis of allowable current injection is required for practical implementation.

The influence of the interface region is examined for each of the electrode arrays presented in Figure 4.3. Since it is unclear as to the most advantageous electrode array, the analysis is broken up into two parts by examining the current injection/retrieval electrodes (A and B) and the electrical potential measuring electrodes (M and N), separately, under the same interface region conditions. To do this, this analysis will rely on two types of ground conditions similar to those presented in Chapter 2 for a planar difference moving towards a surface-based electrical resistivity array. Figure 4.4 shows the ground conditions used in the finite element models.

In Figure 4.4(a), the TBM is operating in a homogeneous earth condition where the electrical conductivity of the earth is assigned a value of $\sigma$. This condition is used to evaluate each model combination (TBM type, interface region assumption, and electrode configuration) for maximum current density penetration distance (consistent with the $z_{\text{max}}$ current density analysis from Chapter 2). The direction of interest is horizontal ($x$) and in the direction of excavation. $x_{\text{max}}$ is used to define maximum current penetration distance.
Figure 4.3: Six unique electrode arrays for TBM-integrated electrical resistivity with qualitative current flow lines

In Figure 4.4(b), the TBM is surrounded in a homogeneous earth condition $\sigma_1$ and is approaching a homogeneous material $\sigma_2$ at a distance $x_D$ ahead of the TBM. The planar difference is moved closer to the TBM and the sensitivity of the potential measuring electrodes is observed for each model combination (both electrode configuration and assumption for the interface region). The sensitivity to the planar difference is analyzed for two conditions:
1. $\sigma_1 = 10^{-2}$ S/m and $\sigma_1 = 10^{-1}$ S/m (low conductivity to high conductivity)

2. $\sigma_1 = 10^{-1}$ S/m and $\sigma_1 = 10^{-2}$ S/m (high conductivity to low conductivity)

Figure 4.4: Modeled ground conditions (a) TBM in a homogeneous ground condition, (b) TBM in a homogeneous ground condition, $\sigma_1$, approaching a homogeneous infinite vertical planar difference, $\sigma_2$

4.4 Finite Element Model

Finite element models were developed to perform the analysis in the following sections. Models were constructed and run using COMSOL Multiphysics. COMSOL uses physics-based partial differential equations to observe physical phenomenon in three-dimensional space. This study simulates electrical flow through the model as it interacts with geometries (volumes, surfaces and points) given defined values of electrical conductivity and a set magnitude of electrical current injection/retrieval.

Figure 4.5 illustrates the COMSOL model space. Figure 4.5(a) shows the front and center of a tunnel boring machine located in the center $(x,y,z = 0,0,0)$ of a 500m cube, where 5 of six sides use COMSOL’s infinite elements feature to simulate an infinite half-space. The top of the cube is left unaltered to simulate any boundary effects from an actual ground surface. Figure 4.5(b) shows an $x$-$z$ vertical cross section $(y=0)$ of the TBM.

The TBM is given a diameter and shield length equal to $D$. The shield and cutterhead are given a thickness of 0.5m as shown in Figure 4.5(b). The 0.5m thickness of the cutterhead
is reasonable in size for a 10m diameter machine. The 0.5 thickness for the shield is thicker than normal and was intentionally done to try and capture the many intricacies of a real TBM. As detailed in Chapter 1, the TBM is made up of the cutterhead, shield and trailing gear. Since the trailing gear (largely made up of a metal) was not included specifically in the model TBM, the extra thickness of the shield was given to try and incorporate a larger volume of metal into the models for more accurate current flow in the space around the TBM structure. The TBM in Figure 4.5 does not reflect a specific machine type (hard rock, EPB or slurry) and associated interface region, but is incorporated in the manner illustrated in Figure in Figure 4.2.

![Figure 4.5: Finite element model setup for tunnel boring machine within an infinite half-space.](image)

For an electrode array that utilizes a cutting tool for either current injection or potential measurement, the electrode is simulated as a 0.25m cube with a 0.05m layer of electrical insulation between itself and the TBM. The thickness of the insulating layer is inconsequential to the modeling results. The consequence of not insulating the cutting tool from the TBM results in a short circuit back to the TBM.

Tetrahedral elements of a minimum size 0.2m and a maximum size 3m were used to mesh the TBM (shield, cutterhead, tunnel lining etc.). Tetrahedral elements of minimum size 3m and maximum size 17.5m were used for the earth around the TBM with the exception of the
“AOI” or area of interest (AOI; shown in Figure 4.5(a)). The AOI is a rectangular prism located directly in front of the TBM and extends to the far right side of the model ($x > 0$). The AOI is created to provide a finer mesh in front of the TBM in order to mitigate coarse mesh averaging close to the electrode array. The AOI is dimensioned 30m by 30m by 250m and is given minimum and maximum tetrahedral element sizes of 0.1m and 3m, respectively.

For these models, a current injection (A) and current sink (B) use current magnitude of 15A, which is consistent with the value determined in Chapter 2 for a theoretical maximum level of safe current injection. The current is injected through the entire volume of the electrodes (even where there is a large volume contrast between current source for integral and scan configurations) and is representative of a field measurement.

4.5 Current Density Analysis

Current density contour plots convey how well each electrode array can inject current ahead of the TBM for each of the various interface region geometries and material types. Figure 4.6 shows contour plots of current density (mA/m$^2$) on the vertical $x$-$z$ plane ($y=0$) around the TBM cutterhead for the electrode configuration shown in the center of the plots (configuration from Figure 4.3(a)) and for hard rock tunneling where the interface region is air ($\sigma_A = \sigma_D = 10^{-15}$ S/m). Each of the four contour plots in Figure 4.6 corresponds to each assumption regarding the presence of the interface region, as defined in Figure 4. Current density contours of 10, 7.5, 5, 2.5, and 1 mA/m$^2$ are shown. For reference, the average current densities observed within the formation, just outside the interface region, are shown in Figure 4.6.

Figure 4.6(a) illustrates the current density field for the baseline case where the TBM cutterhead and shield are in direct contact with the ground (i.e. no interface region). In this baseline case, current propagates into the ground in a spherical manner around the TBM. As current propagates from its source (in this case the cutterhead and shield), current density decays with $x$ due to geometrical spreading. The current density of 33 mA/m$^2$ at the cutterhead decays to 7.5 mA mA/m$^2$ at $x \approx 8$m due to geometrical spreading.
Figure 4.6: Current density (mA/m^2) contour plots for electrode configuration Figure 4.3(a), x(m) vs. z(m), around the TBM showing maximum penetration distance, x_{max}(m), for current density contour levels: 10, 7.5, 5, 2.5, 1 mA/m^2. All contour plots shown for homogeneous earth condition (Figure 4.4(a)), and hard rock tunneling (\sigma_A = \sigma_D = 10^{-15} S/m). Assumptions for the interface region configuration as shown in Figure 4.2: (a) no region, (b) disc and annulus, (c) only disc, (d), only annulus.

As shown in Figures 4.6(b), 4.6(c) and 4.6(d), the presence of an air-filled interface region has a significant influence on the distribution of current density around the TBM. In contrast to the baseline case, which distributes current density somewhat evenly around the TBM (due to perfect TBM contact with the formation), cases (b), (c) and (d) distribute current density in a way that is dependent upon the distribution of the interface region.

For example in case (b), the interface region is comprised of both the disk and the annulus. Even though both the disk and the annulus are present, the annulus is given a
thickness that is much smaller than the disk. Therefore, the annulus provides a path of lesser resistance due to its smaller thickness (15cm annulus compared to 40cm disk) and more current density is seen concentrated around the annulus. In this case, prediction ahead of the TBM is reduced because current does not flow as far out in front of the TBM in the x-direction. If the annulus was given a thickness equal to the disk \((t_A = t_D)\), then current would be observed more equally concentrated as the baseline case. For cases (c) and (d), the behavior follows the same logic regarding the dependence of current density distribution on the configuration of the interface region. The case in Figure 4.6(d) shows the greatest current density penetration distance because current is focused through the TBM cutterhead with the absence of the disk.

One aspect that is not clear from Figure 4.6 pertains to current densities observed outside of the interface region in case (b) with a full interface region. In general, these are much lower than for any of the other cases. This is due to a phenomenon not displayed in the subplot. As a result of the interface region entirely encapsulating the outer TBM surface, the path of least resistance is through the back on the TBM and through the grouted region \((\sigma = 10^{-3} \text{ S/m})\) just outside the tunnel lining. Only a fraction of the total injected current escapes through the interface region, and therefore, lower current densities are observed.

In general, if more current can escape out of the disk (as opposed to the annulus or through the grouted lining), then greater values in \(x_{\text{max}}\) can be observed. \(x_{\text{max}}\) and current density \((\text{mA/m}^2)\) information in Figure 4.6 are presented in Figure 4.7(a). The results from all four plots in Figure 4.6 are collapsed into Figure 4.7(a) to show the relative influence of each of the interface region conditions on the electrode array and TBM type (hard rock, slurry and EPB). Figure 4.7(a) confirms the discussion above, where \(t_D, t_A = 0,15\) provides the highest current density penetration and \(t_D, t_A = 40,15\) provides the least current density penetration.

The rest of Figure 4.7 shows the results from simulations using the five remaining electrode configurations from Figure 4.3. Each of the other five electrode configurations are subjected to the four interface region \(t_D, t_A\) combinations and are shown in their respective
subplots. Their associated current density data, like Figure 4.6, are collapsed into plots that compare current density to \( x_{\text{max}} \). Figure 4.7 presents simulation results for hard rock and EPB tunneling (i.e. their plots overlay one another). This is because the differences in influence between the highly resistive air in hard rock tunneling (\( \sigma_A = \sigma_D = 10^{-15} \text{ S/m} \)) and foam conditioned soil in EPB tunneling (\( \sigma_A = \sigma_D = 10^{-6} \text{ S/m} \)) were negligible.

Figure 4.7 shows that current density decays as \( x_{\text{max}} \) is increased and is explained by the geometrical spreading observed from the contour plots in Figure 4.6. Regardless of electrode array or interface region scenario, each curve has relatively the same shape of decay. The difference between each curve is a horizontal shift in \( x_{\text{max}} \) that is dependent upon the proportion of current density leaving through the disk compared to the annulus. After current escapes the interface region, current must flow through the same homogeneous formation and the current flow behavior must be the same outside of the interface region.

For open mode (hard rock) and EPB TBM tunneling, current density propagation is influenced more for electrode configurations that inject current from the entire TBM cutterhead and shield (Figure 4.7(a), 4.7(b) and 4.7(c)) because they allow for such large areas of the current source (A) to be isolated from the formation by the interface region. Electrode configurations that inject current from a single isolated cutting tool allow for less influence as the cutting tool has a smaller surface area to influence, is electrically isolated from the TBM, and always has at least partial contact with the formation. In comparison to configurations that inject through the entire cutterhead and shield, cutting tool injection actually benefits from the electrical insulation of the TBM by the interface region. If the interface region is not entirely present (i.e. full electrical isolation of the TBM from the formation), then current is drawn back to the highly conductive TBM.

Figure 4.8 provides values of \( x_{\text{max}} \) for a range in current density (from 1 to 10 mA/m²) for slurry TBM tunneling where the interface region \( \sigma_A = \sigma_D = 10^0 \text{ S/m} \). In contrast to the hard rock and EPB models, the slurry TBM models assign an interface region electrical conductivity that is
greater than that of the formation (here by one order of magnitude). Even though one order of magnitude is significant, the interface region thickness is not large enough to influence the results for a slurry TBM. In these cases, all four assumptions for the interface region tend to overlap one another or are otherwise very closely spaced. In comparison to hard rock and EPB TBMs, Figure 4.8 suggests that $x_{\text{max}}$ is not significantly influenced by the electrode array or assumption for the interface region. For slurry tunneling, the ability to propagate current density rests within the low and high range of hard rock and EPB tunneling where the case of $t_D, t_A = 0,0$ for hard rock or EPB tunneling is consistent with values observed for slurry tunneling.

### 4.6 Potential Measurement Sensitivity Analysis

This section analyzes the influence of the interface region on the electrical potential measuring electrodes M and N, particularly the sensitivity of the potential measurement to a vertical planar difference ahead of the TBM cutterhead. In reality, there exist many forms of geologic differences including boulders, karstic voids – water or air filled, seams, faults or water bearing regions. These geologic differences are not explicitly considered here.

Figures 4.9 through 4.12 present the change in measured potential $\Delta V_{MN}$ as the TBM approaches a vertical planar difference in the formation ahead of the TBM. In these plots, the change in potential $\Delta V_{MN}$ is with respect to far-field condition, i.e., $V_{MN} - V_{\text{FAR FIELD}}$. $\Delta V_{MN}$ vs. $x_D$ is shown for each interface region configuration (e.g. $t_D, t_A = 40,15$) and material property (e.g. $\sigma_A = \sigma_D = 10^{-15}$ S/m). Sub-plot (a) presents the condition where the formation in which the TBM resides has $\sigma_1 = 10^{-2}$ S/m, and the formation at a distance $x_D$ in front of the TBM has $\sigma_2 = 10^{-1}$ S/m. Sub-plot (b) presents the reverse condition.

In the subfigures (Figures 4.9(a)-4.12(a)) $\Delta V_{MN}$ becomes increasingly negative as $x_D$ decreases. This result is due to the approaching planar difference that is more conductive than the formation around the TBM. As the TBM advances toward to the planar difference, the observed electrical conductivity around the TBM continues to increase (i.e., current is more
attracted to the planar difference) and therefore, the measured electrical potential must continue to decrease - this results in negative values for $\Delta V_{MN}$.

**Figure 4.7**: Maximum penetration distance, $x_{\text{max}}$ (m), of current density (mA/m$^2$) in front of cutterhead ($x>0$) for hard rock and EPB tunneling, (a) Figure 4.3(a) electrode configuration, (b) Figure 4.3(b) electrode configuration, (c) Figure 4.3(c) electrode configuration, (d) Figure 4.3(d) electrode configuration, (e) Figure 4.4(e) electrode configuration, (f) Figure 4.3(f) electrode configuration
Figure 4.8: Maximum penetration distance, \( x_{\text{max}} \) (m), of current density (mA/m\(^2\)) seen in front of TBM cutterhead (x=0) for slurry shield tunneling, (a) Figure 4.4(a) electrode configuration, (b) Figure 4.3(b) electrode configuration, (c) Figure 4.3(c) electrode configuration, (d) Figure 4.3(d) electrode configuration, (e) Figure 4.3(e) electrode configuration, (f) Figure 4.3(f) electrode configuration.
The opposite is true for the subfigures (Figures 4.9(b)-4.12(b)) where a more resistive planar difference effectively creates a lower electrical conductivity (i.e., the current is repelled by the planar difference) and $\Delta V_{MN}$ must continue to increase. Much like the analysis performed in Chapter 2, when $x_D$ is sufficiently large, the planar difference has no effect on the measurement $V_{MN}$ and so $V_{MN} = V_{FAR\ FIELD}$. If a change is detected (i.e. $\Delta V = V_{MN} - V_{FAR\ FIELD} \neq 0$), then the planar difference has been detected for its position $x_D$. This value of $x_D$ is called the ‘look-ahead distance’ or $x_L$. For example in Figure 4.9(a), the condition of $t_D, t_A = 0, 15$ yields a look-ahead distance of $x_L \approx 40$. This suggests that this electrode array is capable of identifying a planar difference for $x \leq 4$. The look-ahead distances observed in these plots are only theoretical; in reality, electrical noise and ground heterogeneity would reduce a realizable look-ahead distance.

The figures demonstrate that the $\Delta V_{MN}$ vs. $x_D$ is influenced by the interface region. For example in Figure 4.9, the look-ahead distance is greater for the focusing configuration ($t_D, t_A = 0, 15$) than any of the others, and the configuration with air-filled annulus and disk interface regions ($t_D, t_A = 40, 15$) exhibits a lesser look-ahead distance consistent with the limited current density propagation shown in Figure 4.6. For all cases in Figure 4.9(a), the observed look-ahead distances are considerable and at least $x_L = 20$ for all assumptions of the interface region. To place this 20m look-ahead distance in context, typical ring advances are 1.5-2.0m and take 30-45 minutes to advance and build. A 20m look-ahead distance equates to 10-13 rings and 6-10 hours advance warning.

For all plots in Figures 4.9 through 4.12, the condition for hard rock ($\sigma_A = \sigma_D = 10-15$ S/m) and EPB ($\sigma_A = \sigma_D = 10-6$ S/m) TBM tunneling shows results that are identical, where plots of $\Delta V_{MN}$ vs. $x_D$ overlap each other. Further, slurry TBM tunneling is not significantly influenced by the interface region. Both of these results are consistent with the behavior observed in the current density vs. $x_{max}$ plots shown in Figures 4.7 and 4.8.

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In Figures 4.9 through 4.12, only the electrode configurations that positioned the current sink behind the TBM ($x < 0$) were shown. For Figures 4.13 and 4.14, electrode configurations that position the current sink in front of the TBM ($x > 0$) are shown. Subplots (c) and (d) are zoomed-in plots of (a) and (b), respectively. For smaller $x_D$ values, subplots (c) and (d) are visually similar to those presented in Figures 4.9 through 4.12. As $x_D$ decreases, $\Delta V_{MN}$ intensifies. However, subplots (a) and (b) reveal an intermediate region for values of $x_D$ where $\Delta V_{MN}$ remains constant at a magnitude that is non-zero. As $x_D$ increases to a value of 24, $\Delta V_{MN}$ approaches zero.

This behavior can be explained by the flow of current through the model and is qualitatively explained by the current flow lines shown by the electrode configurations in Figure 4.3. Methods which position the current sink behind the TBM, draw current behind the TBM after it escapes into the formation. This causes there to be near zero current densities at significant distances in front of the TBM (e.g. $x > 30$ m for Figure 4.6(a)). When the planar difference crosses into a region that holds significant current density, a non-zero $\Delta V_{MN}$ is recorded. For the cases where the sink is located behind the TBM, there is only one region of significant current density in front of the TBM ($x > 0$). This region is shown the Figure 4.6 plots. When the current sink is positioned in front of the TBM, all of the current is forced to flow in front of the TBM and to the sink at the surface, thereby creating two concentrated regions of current density: 1) directly in front of the TBM and 2) far away at the current sink. These two concentrated regions produce the two regions of changing $\Delta V_{MN}$ that can be observed in Figures 4.13 and 4.14.

For Figure 4.13 and 4.14, the look-ahead distance is more straight-forward to identify in subplots (c) and (d) but there may be difficulties in the field when the location of planar difference is uncertain (i.e. TBM operator does not know if the planar difference is located close to the sink or if it is close to the TBM). For this analysis, the look-ahead distance is determined by using the changing $\Delta V_{MN}$ region that is closest to the TBM as shown in subplots (a) and (b).
The changing $\Delta V_{MN}$ region nearest the current sink should be considered a false positive for detection and should be disregarded.

Figure 4.9: Electrical potential sensitivity to an infinite, vertical planar difference, located at $x_D$, for electrode configuration from Figure 4.3(a): (a) $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m, (b) $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m

Figure 4.10: Electrical potential sensitivity to an infinite, vertical planar difference, located at $x_D$, for electrode configuration from Figure 4.3(c): (a) $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m, (b) $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m
Figure 4.11: Electrical potential sensitivity to an infinite, vertical planar difference, located at $x_D$, for electrode configuration from Figure 4.3(d): (a) $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m, (b) $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m

Figure 4.12: Electrical potential sensitivity to an infinite, vertical planar difference, located at $x_D$, for electrode configuration from Figure 4.3(f): (a) $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m, (b) $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m
Figure 4.13: Electrical potential sensitivity to an infinite, vertical planar difference, located at $x_D$, for electrode configuration from Figure 4.3(b): (a) $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m, (b) $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m
Figure 4.14: Electrical potential sensitivity to an infinite, vertical planar difference, located at $x_D$, for electrode configuration from Figure 4.3(e): (a) $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m, (b) $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m

The previous $\Delta V_{MN}$ vs. $x_D$ plots present a large amount of information and it is difficult to point to the best combination of electrode array, interface region assumption, and TBM type.

Tables 4.1 and 4.2 summarize look-ahead distances for each combination.
In general, the cases where the TBM moves toward an incoming conductive difference \((\sigma_1 = 10^{-2} \text{ S/m and } \sigma_2 = 10^{-1} \text{ S/m})\) exhibit the best look-ahead distances. Even though hard rock and EPB tunneling show greater look-ahead distances on average compared to slurry tunneling, slurry tunneling shows no influence on look-ahead distance for the interface region and may be the more reliable choice for TBM-integrated-electrical resistivity.

**Table 4.1**: Estimated look-ahead distances for each Figure 4.3 electrode configuration and each assumption for the interface region. Ground condition in front of TBM shown for \(\sigma_1 = 10^{-2} \text{ S/m and } \sigma_2 = 10^{-1} \text{ S/m}\) from Figure 4.4. Distances shown in terms of dimensionless distance in front of TBM, \(x_D\), in TBM diameters.

<table>
<thead>
<tr>
<th>Electrode Configuration</th>
<th>Look-Ahead Distance (Diameters of TBM)</th>
<th>(\sigma_1 = 10^{-2} \text{ S/m})</th>
<th>(\sigma_2 = 10^{-1} \text{ S/m})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Rock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°/0°</td>
<td>3.50</td>
<td>3.50</td>
<td>3.75</td>
</tr>
<tr>
<td>40°/15</td>
<td>1.50</td>
<td>3.00</td>
<td>5.00</td>
</tr>
<tr>
<td>40°/0°</td>
<td>3.50</td>
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<td>3.75</td>
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<tr>
<td>0°/15</td>
<td>4.00</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>EPB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°/0°</td>
<td>3.50</td>
<td>3.50</td>
<td>3.75</td>
</tr>
<tr>
<td>40°/15</td>
<td>1.50</td>
<td>3.00</td>
<td>5.00</td>
</tr>
<tr>
<td>40°/0°</td>
<td>3.50</td>
<td>3.50</td>
<td>3.75</td>
</tr>
<tr>
<td>0°/15</td>
<td>4.00</td>
<td>4.00</td>
<td>4.00</td>
</tr>
<tr>
<td>Slurry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°/0°</td>
<td>3.50</td>
<td>3.50</td>
<td>3.75</td>
</tr>
<tr>
<td>40°/15</td>
<td>3.50</td>
<td>3.50</td>
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<tr>
<td>40°/0°</td>
<td>3.50</td>
<td>3.50</td>
<td>3.75</td>
</tr>
<tr>
<td>0°/15</td>
<td>3.50</td>
<td>3.50</td>
<td>3.75</td>
</tr>
</tbody>
</table>

**Table 4.2**: Estimated look-ahead distances for each Figure 4.3 electrode configuration and each assumption for the interface region. Ground condition in front of TBM shown for \(\sigma_1 = 10^{-1} \text{ S/m and } \sigma_2 = 10^{-2} \text{ S/m}\) from Figure 4.4. Distances shown in terms of dimensionless distance in front of TBM, \(x_D\), in TBM diameters.

<table>
<thead>
<tr>
<th>Electrode Configuration</th>
<th>Look-Ahead Distance (Diameters of TBM)</th>
<th>(\sigma_1 = 10^{-1} \text{ S/m})</th>
<th>(\sigma_2 = 10^{-2} \text{ S/m})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Rock</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°/0°</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>40°/15</td>
<td>1.00</td>
<td>0.25</td>
<td>1.50</td>
</tr>
<tr>
<td>40°/0°</td>
<td>1.00</td>
<td>0.75</td>
<td>1.00</td>
</tr>
<tr>
<td>0°/15</td>
<td>1.50</td>
<td>1.50</td>
<td>1.25</td>
</tr>
<tr>
<td>EPB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°/0°</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>40°/15</td>
<td>1.00</td>
<td>0.25</td>
<td>1.50</td>
</tr>
<tr>
<td>40°/0°</td>
<td>1.00</td>
<td>0.75</td>
<td>1.00</td>
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<tr>
<td>0°/15</td>
<td>1.50</td>
<td>1.50</td>
<td>1.25</td>
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<tr>
<td>Slurry</td>
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</tr>
<tr>
<td>0°/0°</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>40°/15</td>
<td>1.00</td>
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<tr>
<td>40°/0°</td>
<td>1.00</td>
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<tr>
<td>0°/15</td>
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<td>1.00</td>
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</tr>
</tbody>
</table>
4.7 Conclusions

This chapter presents finite element results from a three dimensional study on electrical resistivity methods applied to the TBM tunneling environment. We focus on identifying the electrical influence of a volume that interfaces the TBM to the virgin formation, called the interface region. There is a degree of uncertainty regarding the interface region regarding its electrical conductivity and geometry and so this study considers a range in each. Six electrode arrays are considered that are unique to TBM-integrated-electrical resistivity in an attempt to understand the influence of the interface region to a number of possible implementations in the field. The following conclusions can be drawn from the findings:

- For all six electrode configurations, significant current densities (>1mA/m²) can be observed out to 30 m ahead of the 10 m diameter cutting face when the TBM is perfectly coupled to formation (i.e. no interface region). When the interface region is introduced, it has a varying amount of influence on the ability of current density to propagate in front of the TBM. The influence of the interface region is dependent upon the method of the current injection (i.e. full TBM body or isolated cutting tool) as well as the TBM type (i.e. hard rock, EPB and slurry).

- Electrode configurations that inject current from the entire TBM body (cutterhead and shield) are negatively influenced by the presence of the interface region because it isolates the injection electrode from the formation. Current density propagation distance is decreased by as much as 30% depending upon the configuration of the interface region. The exception to this is when the interface region consists only of the annulus, in which case current is focused through the cutterhead and current density propagation is increased by approximately 20%.

- Electrode configurations that inject current from a single isolated cutting tool are positively influenced by the interface region where current density propagation is increased by approximately 20%. The best case scenario for these electrode
configurations is given when the TBM is completely encapsulated by the interface region, effectively shielding the large metal structure from the formation. In contrast to full TBM body injection, cutting tool injection demonstrates less of a range in influence to the interface region.

- Hard rock and EPB tunneling conditions offer identical observations for both current density propagation ahead of the TBM as well as $\Delta V_{MN}$ measurements taken for an incoming vertical planar difference.
- For slurry tunneling, the interface region has near zero influence on either current propagation ahead of the TBM or $\Delta V_{MN}$ measurements taken for an incoming vertical planar difference. This result is advantageous as the interface region is not a variable in electrical resistivity analysis throughout the excavation of the tunnel.
- Electrode arrays that position a current sink on the surface, in front of the TBM, show two regions of sensitivity due to the concentration of current density around the sink. In the field, these electrode arrays may be infeasible to implement and this result may provide a false positive detection of a change ahead of the cutting face.
- Electrical resistivity is more sensitive to an incoming vertical planar difference that is more conductive than for one that is more resistive than the formation surrounding the TBM.
- Simulations suggest that TBM-integrated-electrical resistivity can detect a planar difference in geology up to five diameters in front of the TBM. This look-ahead distance is subject to change for other types of geologic/man-made differences ahead of the TBM due to their contrasting size, location and electrical properties.
CHAPTER 5
FULL SCALE COMPUTATIONAL STUDY OF ELECTRICAL RESISTIVITY APPLIED TO TBM TUNNEL ENVIRONMENT FOR THE PREDICTION OF VARIOUS CHANGES AHEAD OF THE TUNNEL FACE

5.1 Introduction

TBM tunnel excavations are susceptible to unanticipated geologic and man-made changes ahead of the machine, particularly smaller anomalies that go undetected during initial site investigation. When unanticipated changes are encountered by the machine, significant machine damage and project costs can be incurred. For example, a boulder in soft ground can shear cutting tools from the cutterhead causing the need for immediate replacement and therefore a cease in excavation. Additionally, a sand lens in clay causes a region of higher permeability and so can result in ground water inflows if face pressure conditions are not appropriately set. When electrical conductivity contrasts exist between varying ground conditions, electrical resistivity applied to the TBM tunnel environment provides a means of detecting changing ground conditions before they are encountered.

Building from the previous chapter, which investigated the influence of the interface region in predicting a vertical planar difference, this chapter focuses on two of the six electrode arrays for detecting various changes ahead of the TBM. In this chapter, the interface region is not considered in this study and so the TBM is assumed to make perfect physical contact with the formation. The interface region was not considered as the study showed that the interface region demonstrated a scaled effect based upon TBM type (i.e., once current passed through the interface region it behaved in the same manner). Furthermore, the study of the interface region aimed to evaluate a ranged influence of its theoretical presence around the TBM. It is not clear which configuration or material properties of the interface would exist for a particular tunnel or is correct, and so, a case where no interface region exists allows for a constant means for
comparison of data for the following study. In the event where the interface region is present, the results shown here would scale according to the findings presented in the previous chapter.

Similar to the previous study, this study will fix a material conductivity contrast at a magnitude of ten except for when a metal pipe is evaluated. The simulations in this chapter will use a magnitude of current injection of 15 Amps, which is consistent with the evaluated level of safe current injection analyzed in Appendix B. Mooney et al. [18] evaluated the look-ahead distance for a vertical planar difference and vertical planar inclusions. Both changes are reevaluated here. A noise threshold of 1V is used to determine the look-ahead distance and is expected to be very conservative but allows for a consistent comparison of data for different changes ahead of the TBM.

The simulations presented, use computational finite element modeling to simulate various geologic changes or metal pipe in front of the TBM. Two of the six electrode configurations from the Chapter 4 are evaluated, herein called integral mode and scan mode adopted from the BEAM and BEAM4 commercial systems (e.g., [1]). It should be noted that these two configurations will be used and referred to consistently as integral mode and scan mode for the remainder of this dissertation.

5.2 Geologic and Man-Made Differences Ahead of the Tunnel Boring Machine

Conditions ahead of the tunnel boring machine can present themselves in many different ways and can be either geologic (natural) or man-made (e.g., foundation remnants, tiebacks, utilities). In either case, if unanticipated conditions are encountered and not prepared for accordingly, serious damage to the TBM can occur.

Figure 5.1 presents illustrations of several possible changes that are simulated in this study. Each change is positioned in front of the TBM at a distance $x_D$ defined from the center of the of tunnel alignment (except for a lens located at the tunnel crown). For each of the geologic conditions presented in the figure, the electrical conductivity around the TBM is given $\sigma_1 = 10^{-2}$ S/m and the geologic change is given $\sigma_2 = 10^{-1}$ S/m. These values could be representative for
the TBM moving from a saturated sand to a saturated clay, or from a moist clay to a saturated sand. In the case when the TBM moves toward a metal pipe, $\sigma_1 = 10^{-2} \text{ S/m}$ and $\sigma_2 = 10^6 \text{ S/m}$, which is consistent for the electrical conductivity of steel. Each of the geologic differences is modeled on-center of the face of the TBM (excluding the lens located at the tunnel crown). In order to determine the influence of a laterally offset change ahead of the TBM, this chapter evaluates two different lateral locations of the metal pipe (Figure 5.1(h)).

![Figure 5.1 Geologic and man-made differences ahead of the tunnel boring machine](image-url)
5.3 Finite Element Model Set-Up

Computational finite element modeling is used to evaluate the ability of an electrical resistivity array to predict a change (geologic and pipe) ahead of the TBM. Models were constructed and run using COMSOL Multiphysics with the same specifications as defined in Chapter 4. The model space is shown here again in Figure 5.2.

Figure 5.2 illustrates the COMSOL model space. Figure 5.2(a) shows the front and center of a tunnel boring machine located in the center \((x,y,z = 0,0,0)\) of a 500m cube. The TBM in the illustration does not reflect a specific machine type (hard rock, EPB or slurry). The reader should note that the influence of the interface region was analyzed in Chapter 4 and so this chapter does not incorporate it into the simulations. For these simulations, the TBM is assumed to make perfect electrical contact with the surrounding formation, \(\sigma\).

![Figure 5.2: Finite element model setup for tunnel boring machine within an infinite half-space.](image)

Figure 5.3 illustrates the two unique electrode arrays used in this analysis. In contrast to the experimental simulations in Chapter 3, integral mode and scan mode arrays were modified based on insight from computational models and knowledge gained from industry discussion regarding feasible implementation. The configuration in Figure 5.3(a) will be called integral mode. The configuration is Figure 5.3(b) will be called scan mode. These names will be
applicable for this chapter as well as Chapter 6, which investigates the geometry and boundary conditions of the TBM, tunnel, and electrode array.

![Figure 5.3: Electrode resistivity array integrated into tunnel boring machine (TBM) used for prediction analysis of geologic/man-made difference in front of tunnel face, (a) TBM shield + cutterhead as injection electrode called ‘integral mode’, (b) cutting tool as injection electrode called ‘scan mode’](image)

The diameter of the TBM and shield length are given a value of \( D = 10 \text{m} \). The alignment of the tunnel is positioned in the center of the model space for a cover \( C = 245 \text{m} \), which is sufficiently high to help negate any boundary effects in this model. It is expected that the ground surface plays a role in the prediction of changes ahead of the TBM through the constriction of current flow above the tunnel crown. This will be highlighted in Chapter 6.

In both electrode arrays, the electrical current sink (B) and the potential measuring electrode (N) are the same and consist of points that model metal stakes that are inserted through a tunnel lining and into the earth. These electrodes are placed at the edge \( x = -250 \text{m} \) of the model space at the infinite condition. As opposed to the experimental design from Chapter 3, this chapter does not use symmetric rings for electrical potential (N) measurement and current retrieval (B). Although ideal for symmetry of current flow, these rings are not feasible for field investigations.

Integral mode uses the entire TBM (cutterhead and shield) for a current injection and a second point electrode for potential measurement (M), located one meter behind the TBM
shield. Scan mode uses cutting tools for current injection (A) and potential measurement (M).
For scan mode electrodes A and M are placed near the edge of the TBM cutterhead with a center-to-center separation equal to 9m.

For these models, a current injection (A) and current sink (B) use current magnitude of 15A, which is consistent with the value determined in Appendix B for a theoretical maximum level of safe current injection. The current is injected through the entire volume of the electrodes (even where there is a large volume contrast between current source for integral and scan configurations) and is representative of a field measurement.

5.4 Results and Analysis
Each of the geologic changes and pipe were evaluated by incrementing the change a toward the TBM (decreasing values of $x_D$). At each increment, the voltage, $V_{MN}$, is measured between electrodes M and N. In accordance with the discussion from Chapter 2, the experimental analysis in Chapter 3 and the finite element analysis in Chapter 4, $V_{FAR-FIELD}$ is subtracted from each $V_{MN}$ to create a graph of $\Delta V$.

Figure 5.4 shows the modeling results for a vertical planar inclusion and a vertical planar difference ($a \rightarrow \infty$). An electrical noise threshold is set at 1V. Since it is not well understood, the electrical noise threshold of 1V is completely arbitrary, but is set as a constant for these simulations in order to compare $\Delta V$ for a) both electrode arrays and b) the entire list of changes ahead of the TBM modeled in this study.

The inclusion causes a measurable decrease in $\Delta V$ as the injected current is drawn into the more conductive inclusion. Recall that Chapters 2 (surface-based array) 3 and 4 (experimental and computational TBM look-ahead) showed this same behavior for an incoming difference that is more conductive and acts to draw electrical current away from the electrode array. This serves to decrease the current density at the point of potential measurement (M) and therefore decreases the potential difference.
For both integral and scan mode, as the size of the vertical planar inclusion is increased (increasing value in $a$), $\Delta V$ overcomes the 1V noise threshold at larger values of $x_D$. For example, when integral mode is used, for a planar inclusion thickness of $a = 0.5$, a signal to noise ratio of 1 is observed at approximately $x_D = 3m$ (0.3 TBM diameters). At this location of the vertical planar inclusion, $x_D$ is equal to the look-ahead distance, $x_L$. When $a \to \infty$, $x_L$ is increased to $27m$ (2.7 TBM diameters) giving an increased look-ahead distance of 900% percent. This result is due to the increase in volume of the change ahead of the TBM. As the volume of the planar inclusion grows, it will have more of an influence to draw electrical current as it approaches the current source. Though not shown here, $x_L$ increases with conductivity contrast as shown in Mooney et al. [18].

Similar behavior is observed for scan mode, however, it presents an increased prediction capacity when compared to integral mode. In scan mode, when $a \to \infty$, $x_L = 33m$, it provides an additional 0.6 tunnel diameters (i.e., 6m) of prediction for the same incoming anomaly. This small advantage is due to the difference in geometry of the electrode arrays. In Chapter 3, the experimental results showed effectively no differences between scan and integral mode for $\Delta V$ vs. $z_D$ (in this case $x_D$) due to the symmetry of the arrays. In these cases, the array are not symmetric and so clearly, the geometry of scan mode has an advantage over integral mode when the electrode geometry is asymmetric. This geometric advantage will become apparent for finite anomalies (e.g., lens, pipe) presented later in this chapter.

Figure 5.5 shows the model results for the TBM moving toward a horizontal seam. These figures show a result that is similar to that from Figure 5.4 for a vertical planar inclusion. As the size, $a$, of the horizontal seam is increased, the look-ahead distance is also increased. A similar advantage is given to scan mode over integral mode.

In contrast to Figure 5.4, lower values in $x_L$ are observed for similar values in $a$ (e.g., $x_L = 6m$ at $a = 1.0m$ in Figure 5.4a, $x_L = 1m$ at $a = 1.0m$ in Figure 5.5a). Again, this can be attributed to the size of the change ahead of the TBM. Since the horizontal seam holds a lower volume for
the same values in $a$ (compared to the vertical inclusion), it has a smaller influence on the flow of electrical current ahead of the TBM. In both subfigures, when the horizontal seam has a thickness of $a = 0.5m$, the geologic change goes undetected by the electrode array because of a signal to noise ratio less than unity. Recall that the noise amplitude for these simulations is set to be conservative and so in a field investigation, a seam of the same thickness could be detected in lower noise situations.

Figure 5.6 presents the $\Delta V$ vs. $x_D$ for an angled planar difference ahead of the TBM with an incline of $\theta$ (degrees) from the horizontal ($x$-$y$ plane). As $\theta$ is increased, $x_L$ decreases. Since $x_D$ is measured from the center of the TBM, an angled difference that is relatively flat will move below the TBM before it is encountered in the excavation alignment. Recall from Chapter 4, that the current flow lines move around the TBM and back to the sink along the tunnel lining. The current that flows around the TBM and back to the current sink, B, is therefore influenced by the angled difference even though the TBM may not excavate the angled difference for 10’s of meters. For example, when $\theta = 15^0$, $x_L = 85m$ (or 8.5 tunnel diameters). Even though the TBM may not excavate the angled difference for another 85m, the plane continues to rise toward the tunnel invert just 23 meters below. It is expected that anomalies not ahead of the TBM, but around the TBM can create a false positive for the identification of a change ahead of the TBM. In these cases, plots of voltage (or apparent resistivity) are insufficient and inversion algorithms are required for accurate prediction ahead of the face.

Figure 5.7 shows the $\Delta V$ vs. $x_D$ results for an incoming lens located at the crown of the tunnel ($z = 5m$). The geometry of the lens is defined as an ellipse (height of $a$ and length of $b$) with an infinite depth in the $y$-direction (into the page). Analogous to previous simulations, the results show that the look-ahead distance is proportional to the lens volume. The largest lens ($a = 10m$, $b = 5m$) in integral mode gives a look-ahead distance of 6m, while the smallest lens ($a = 10m$, $b = 1m$) does not surpass a signal to noise ratio of one.
An interesting finding of these lens simulations lies in the comparison of scan mode and integral mode. In comparison to the previous differences (inclusion and seam) ahead of the TBM, the lens acts more like a finite anomaly as opposed to a macro difference in front of the TBM. Here, the use of a contour plot helps to visualize the anomaly in front of the tunnel face similar to the contour plots of $\Delta V$ shown for the pipe in Chapter 3. By just comparing the $\Delta V$ vs. $x_D$ curves in Figure 5.7, it can be seen that scan mode clearly has an advantage over integral mode. The following contour plot in Figure 5.8 shows why scan mode has the advantage and ultimately rests in ideal positioning of the potential measuring electrode, $M$.

Figure 5.8 shows a y-z cross section ($x = 0.25m$; location of the front of the cutting tool) of $\Delta V$ for when $x_D = 0.5m$. A body of electrical conductivity contrast, such as the lens, influences the electrical current flow (or the electrical field) within its proximity. As the TBM increments toward the lens, the conductive lens will continuously draw more current towards itself and therefore will create a negative $\Delta V$ anomaly. The closer the physical measurement is to the lens, the more negative the $\Delta V$ is measured. At the crown of the tunnel, a negative concentration of $\Delta V$ is shown outlining the lens. Recall from the experimental Chapter 3 where the contour plots of $\Delta V$ for the rod held a negative concentration of $\Delta V$ in the center of the contour plots revealing its orientation and size.

Since the potential measuring electrode and the lens are both located at the crown of the tunnel in these simulations, the electrode $M$ captures the larger electrical changes at the crown. If electrode $M$ were alternatively located at the invert, it would record values of $\Delta V$ that are nearly zero as shown in Figure 5.8. If the potential measurement electrode were located in the bottom half of the tunnel face (i.e., $z < 0$), then the lens would go undetected through a $\Delta V \approx 0$. 

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Figure 5.4: Change in measured electrical potential, $\Delta V(V)$, for an incoming vertical planar inclusion of depth $a$ as a function of its location ahead of the TBM $x_D(m)$ (a) integral mode (b) scan mode
Figure 5.5: Change in measured electrical potential, $\Delta V(V)$, for an incoming horizontal seam as a function of its location ahead of the TBM $x_D(m)$ (a) integral mode electrode configuration (b) scan mode electrode configuration.
Figure 5.6: Change in measured electrical potential, $\Delta V(V)$, for an incoming diagonal planar difference as a function of its location ahead of the TBM $x_D(m)$ (a) integral mode electrode configuration (b) scan mode electrode configuration
Figure 5.7: Change in measured electrical potential, $\Delta V(V)$, for an incoming lens at the crown as a function of its location ahead of the TBM, $x_D$(m) (a) integral mode electrode configuration (b) scan mode electrode configuration
In reality, the cutterhead will rotate as the TBM advances through the ground and so it is expected that a cutting tool in scan mode will act like a 'fish-finder' to scan the ground for these anomalies, hence the reason for the name scan mode. This is a significant advantage of scan mode over integral mode, however, its implementation in the field is not trivial and require some implementation considerations. Implementation considerations are given in Appendix A.

Figure 5.9 shows the $\Delta V$ vs. $x_D$ results for an incoming boulder of diameter $d$ (m) located in the center of the tunnel alignment cross-section. The boulder here, is given the same electrical conductivity, $\sigma_2$, to hold the contrast constant and compare against other simulations. In reality, a boulder located in some kind of soil (e.g., sand, clay, silt) would not likely yield a higher conductivity that the surrounding soil. Boulders were modeled with a more realistic conductivity contrast given by, $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m. The model data showed that $\Delta V \approx 0$ for any value of $x_D$ and the results were not included. This result is expected as Mooney et
al. [18] showed that a change that is relative resistive is more difficult to detect than a conductive difference.

Given reasonable sizes for larger boulders, a conductivity contrast of ten in these simulations produce very low values in $\Delta V$ for either electrode array (<20mV changes). With these results, it is expected that in a noisy field setting even with larger injection currents of 15A, individual boulders would likely go undetected without means to focus electrical current in front of the tunnel face.

Figure 5.10 shows the $\Delta V$ vs. $x_D$ results for an incoming vertical metal pipe of diameter $d_{\text{PIPE}} = 0.3m$. Models were analyzed when the pipe was positioned both on center and on the edge of the tunnel alignment. For both electrode arrays, the ability to detect the pipe is best when the pipe is on center. This results makes sense as more electrical current is concentrated to the $x$-$z$, $y = 0$ plane thereby creating a larger electrical potential change when the pipe moves in this plane.

Due to the small size of the pipe ($d_{\text{PIPE}} = 0.3m$), even with a very large conductivity contrast ($\sigma_1 = 10^{-1} \text{ S/m}$ and $\sigma_{\text{PIPE}} = 10^6 \text{ S/m}$), the ability to detect the pipe is low in three of the four cases shown. In scan mode, the change in electrical potential can be captured with greater resolution of the tunnel face. This is very similar to the behavior seen with a lens at the crown as shown in Figure 5.8. A similar contour plot for the pipe is shown in Figure 5.11.

A contour plot of $\Delta V$ for the $y$-$z$ plane, $x = 0.25m$, is shown in Figure 5.11 for a vertical pipe located at the center of the tunnel face at a distance of $x_D = 0.5m$. Much like the contour plot shown for the lens in Figure 5.8, negative $\Delta V$ is concentrated, but here at the center of the cross section due to the presence of the metallic pipe and is vertically oriented like the pipe in the models. In comparison to the contour plot for the lens, the negative concentration of $\Delta V$ is much narrower for the pipe since the pipe’s diameter is 0.3m as opposed to the 1m thickness of the lens.
Figure 5.9: Change in measured electrical potential, $\Delta V(V)$, for an incoming boulder as a function of its location ahead of the TBM $x_D(m)$ (a) integral mode electrode configuration (b) scan mode electrode configuration
Figure 5.10: Change in measured electrical potential, $\Delta V(V)$, for an incoming metal pipe as a function of its location ahead of the TBM $x_D(m)$ (a) integral mode electrode configuration (b) scan mode electrode configuration
Figure 5.11: Cross section of $\Delta V(V)$ on the $y$-$x$ plane ($x = 0.25m$) for a pipe located on the center of the tunnel face at a distance of $x_D = 0.5m$

5.5 Conclusions

This chapter presents finite element results from a three dimensional study on electrical resistivity methods applied to the TBM tunneling environment in order to detect various geologic differences or a metal pipe in front of the TBM. A 10m diameter TBM was placed in a homogeneous condition $\sigma_1 = 10^{-2}$ S/m with a conductive change placed in front of it at a distance of $x_D$ with the condition $\sigma_2 = 10^{-1}$. Various changes were considered including a/an a) vertical planar difference, b) vertical planar inclusion, c) horizontal seam, d) diagonal planar difference, d) lens, e) spherical boulder, f) metallic pipe. Two different electrode configurations were simulated called integral mode and scan mode and are modeled similar to their commercial counterparts from the BEAM and BEAM4 electrical resistivity systems. The following conclusions can be drawn from the study:
• The look-ahead distance is proportional to the volume of the change ahead of the TBM. For example, a vertical planar difference can be predicted further ahead of the TBM than for a vertical planar inclusion.

• In general, scan mode is more successful at predicting a change ahead of the TBM than integral mode, particularly for finite anomalies.

• Scan mode can predict finite anomalies ahead of the TBM because of a significant increase in spatial resolution of voltage measurement at the tunnel face. If multiple cutting tools are used for potential measurement, M, at various radii, as the cutterhead rotates the electrode array will scan the tunnel face for anomalies present directly in front of the TBM.

• The ability to uniquely characterize changes ahead of the TBM may be possible through the process of inversion. The contour plots at the tunnel face for the prediction of a pipe versus a lens at the crown showed significant differences in the distribution of $\Delta V$ due to the conductivity contrast of the change.

• Some smaller anomalies with lower electrical resistivity contrasts (e.g., boulders) may go undetected by electrical resistivity. Current focusing methods should be investigated in order to push more electrical current in front of the TBM to detect smaller changes.
CHAPTER 6

INFLUENCE OF THE TBM TUNNEL ENVIRONMENT AND ELECTRODE GEOMETRY ON ELECTRICAL RESISTIVITY IMAGING

6.1 Introduction

The TBM tunneling environment holds many geometric variables that are subject to change, even during a single project when the tunnel is being excavated. For example, when the TBM initially launches into the earth it may begin 5m below the surface, and in some cases 10’s of meters below the surface. During the excavation, a cover of over 100 meters can be achieved for deep excavations. When electrical resistivity is applied to the TBM tunnel environment, the number of geometric variables only increases and so this leaves a number of uncertainties regarding a best approach for application to the TBM tunneling environment.

While the geometry of the TBM and tunnel are not subject to redesign after the start of excavation, understanding the influence of their role in electrical resistivity measurement is critical for inversion algorithms and interpretation of the electrical field in front of the tunnel face. So far, this dissertation has presented a few different electrode configurations that could be used for electrical resistivity measurements, however, there has been little discussion regarding what happens to the electrical resistivity measurements if there is any relative movement in the electrode array. For example, electrodes B and N model stakes that are pushed through the tunnel lining and remain stationary while the TBM excavates creating a constant increasing separation between the two as the TBM advances.

This chapter highlights several variables related to the TBM/tunnel and electrode array geometry and tests each one in order to understand its influence on prediction ahead of the face. To lay the framework for analysis of the electrode array geometry, this chapter first analyzes a simple surface-based electrode array for an incoming planar difference similar to the analysis performed in Chapter 2. Building on well-established theory, this chapter re-introduces
the TBM/tunnel environment and presents the geometric variables evaluated herein. To evaluate each of the variables, this chapter uses computational finite element modeling consistent with previous chapters. The finite element model is presented in brief detail and the results are given. Finally, conclusions are drawn.

6.2 Geometry of a Surface-Based Electrode Array and Prediction of a Planar Difference

In order to lay the framework for discussion of the complex TBM tunneling environment, this chapter analyzed a well-established simple surface-based electrical resistivity array and its ability to predict an incoming planar difference below the surface. Chapter 2 detailed a similar analysis for various conductivity conditions below the surface. This section will reintroduce the surface array and evaluate how electrical resistivity measurements are subject to the electrode geometry.

Figure 6.1 illustrates four uniquely spaced arrays that are fully defined by the relative spacing between sets of electrodes (i.e. $d$, $AM$, $MN$, $NB$). The figure shows current flow lines that model the current flow from electrode A to electrode B. In these models, the magnitude of $I$ is arbitrarily set to 1 Amp (electrode A) and -1 Amp (electrode B). The magnitude of $I$ is inconsequential to this analysis as there is no electrical noise introduced into this system.

Each current flow line shows a percentage of the total injected current passing above that particular line. For example, in Figure 6.1(a) the 85% current flow line defines that 85% of the total current (in this case 85% of 1 Amp = 850mA) flows above this line and only 15% of the total current (150mA) escapes into the earth below this line. The current flow lines are extracted from a well-established analytical model for a point source/sink in an infinite half space (e.g., [65]). An important note about these models specifies that as depth increases ($z = 10$ m, 20m, 30m...) the percentage of current becomes asymptotic – it would take an infinite depth ($z \rightarrow \infty$) to account for 100% of the injected current (i.e., no current at sufficient values of $z$).

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Figure 6.1: Four electrode surface array A, B, M and N with a horizontal planar difference ($\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m) at 10m below ground surface for assortment of electrode spacing: (a) $d = 30m$, $AM = MN = NB$ (b) $d = 30m$, $AM = NB = 5m$, $MN = 20m$ (c) $d = 60m$, $AM = NB = 25m$, $MN = 10m$, (d) $d = 60m$, $AM = NB = 5m$, $MN = 50m$
Upon the introduction of electrical current, an induced electrical field is instantaneously created and is measured as an electrical potential (measured in Volts) between electrodes M and N; the induced electrical field is shown in Figure 6.1 with equipotential lines that are perpendicular to the current flow lines. The relationship between equipotential lines and current flow lines is analogous to flow-nets that describe head loss during water seepage through geomaterials. Equipotential lines in Figure 6.1 are shown only to the extent between electrodes M and N, but would normally exist past electrodes M and N.

In Figure 6.1, a horizontal planar difference in ground material at a depth $z_{PLANE} = 10\text{m}$ is shown where $\sigma_1 = 10^{-2} \text{S/m}$ and $\sigma_2 = 10^{-1} \text{S/m}$. The planar difference could represent the presence of the ground water table (i.e. $\sigma_1 = 10^{-2} \text{S/m}$ is dry/moist sand, and $\sigma_2 = 10^{-1} \text{S/m}$ is saturated sand). The depth of the ground water table is subject to change and so its location could take on any value of $z_{PLANE} \geq 0$; a period of low to high precipitation could lead to increase or reduction of $z_{PLANE}$, respectively. This change in the spatial distribution of $\sigma$ will ultimately lead to a change in the flow of current and consequently a change in $V_{MN}$ (called $\Delta V_{MN}$) If the planar difference is located at a sufficient depth from the surface ($z_{PLANE} \rightarrow \infty$), then it is expected that the plane does not act to influence the flow of electrical current (near zero electrical current at sufficient depths) and therefore, does not influence $V_{MN}$.

As $z_{PLANE}$ is reduced from the infinite condition ($z_{PLANE} \rightarrow \infty$) towards the surface ($z_{PLANE} = 0$), if $V_{MN}$ records a non-zero change in the electric field, then this depth is called the far-field condition or $V_{FAR-FIELD}$. A measurement of $V_{MN}$ is called $\Delta V_{MN}$ when referenced to the far-field condition (i.e. $\Delta V_{MN} = V_{MN} - V_{FAR-FIELD}$). At $z_{PLANE}$ greater than the far-field condition, the measurement cannot sense the presence of the planar difference (i.e. $\Delta V_{MN} = 0$). At $z_{PLANE}$ less than the far-field condition, the measurement is influenced as the planar difference moves towards the surface. ($\Delta V_{MN} \neq 0$).

Figure 6.2 shows $\Delta V_{MN}$ as a function of $z_{PLANE}$ for each electrode array presented in Figure 6.1. The negative values in $\Delta V_{MN}$ reference the observed regional electrical conductivity.
change. As the location of the water table moves towards the surface, the electrode array observes a regional increase in electrical conductivity (i.e. somewhere less than $\sigma_2 = 10^{-1}$ S/m but greater than $\sigma_1 = 10^{-2}$ S/m). Ohm’s law dictates that $\sigma$ is inversely proportional to $V_{MN}$ and so a $V_{MN}$ value referenced to $V_{FAR-FIELD}$ of lesser conductivity will be negative. This behavior is oppositely true if values in $\sigma$ are reversed such that $\sigma_1 = 10^{-1}$ S/m and $\sigma_2 = 10^{-2}$ S/m (i.e., $\Delta V_{MN}$ becomes positive in sign). The following analysis will show that the far-field condition is subject to change depending upon the geometry of the electrode array.

![Figure 6.2: Magnitude of change in electrical potential for a horizontal planar difference ($\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m) at a depth of $z(m)$ for several electrode geometrical configurations](image)

Figure 6.1 illustrates four unique electrode geometries. Figure 6.2 shows $\Delta V_{MN}$ vs. $z_{PLANE}$ for these four geometries as well as several others that are not illustrated. Figure 6.2 shows how each electrode array yields a different value for $V_{FAR-FIELD}$. For example, the electrode array given by Figure 6.1(a) ($d = 30m, AM = MN = NB$) shows a $\Delta V_{MN} = 0$ at $z_{PLANE} = 30m$, whereas the electrode array from Figure 6.1(d) ($d = 60m, AM = NB = 5m$) shows $\Delta V_{MN} =$
0 at approximately $z_{\text{PLANE}} = 60m$. Given the same changing ground conditions, one electrode array is able to detect the planar difference at twice the depth as another. The following discussion will explain how this is possible.

Figure 6.2 shows two prominent relationships between the geometry of the electrode array and its associated far-field condition for the planar difference. The first behavior is in reference to the current source/sink spacing, $d$. As $d$ is increased, with $AM$ and $NB$ being held constant, $V_{\text{FAR-FIELD}}$ is achieved at larger values of $z_{\text{PLANE}}$. This is exemplified between the two curves: $d = 30m$, $AM = MN = NB$ ($V_{\text{FAR-FIELD}}$ at $z_{\text{PLANE}} = 30m$) and $d = 60m$, $AM = NB = 10m$ ($V_{\text{FAR-FIELD}}$ at $z_{\text{PLANE}} = 55m$). The behavior can be attributed to ability of electrical current to propagate deeper into the earth as illustrated by percent current flow lines shown in Figures 6.1(a) vs. Figure 6.1(c).

The second behavior is in reference to the relative spacing between each neighboring set of a current electrode (either A or B) and a potential measuring electrode (either M or N). If electrodes A and M are considered as a pair (the other pair being B and N), as their spacing is decreased, with $d$ held constant, $V_{\text{FAR-FIELD}}$ can be observed at greater values of $z_{\text{PLANE}}$. This is exemplified between the two curves: $d = 60m$, $AM = NB = 25m$ ($V_{\text{FAR-FIELD}}$ at $z_{\text{PLANE}} = 40m$) and $d = 60m$, $AM = NB = 5m$ ($V_{\text{FAR-FIELD}}$ at $z_{\text{PLANE}} = 60m$).

This behavior can be attributed to the shape of the equipotential lines. Figure 6.1 shows some electrode arrays with M and N located further from A and B, respectively. The equipotential lines measured by M and N appear relatively vertical due to the horizontal nature of current flow towards the center of the array. Given a change in current flow with depth, current lines remain horizontal and so the equipotential lines will remain relatively vertical.

Any changes in current flow (due to contrast in electrical conductivity) allow less change to the equipotential lines towards the center of the array. In fact, at the exact center of each
array \( (d/2) \), the electrical potential is exactly zero \( (V = 0) \) and \( \Delta V_{MN} \) will always be equal to zero. As the equipotential lines move further from the center of the array, they curve away as illustrated in Figure 6.1. This phenomenon fosters larger values in \( \Delta V_{MN} \) when \( M \) and \( N \) move closer to \( A \) and \( B \), respectively.

The previous analysis has shown that \( d \) and \( V_{FAR-FIELD} \) are directly proportional, and that \( AM \) (or \( NB \)) and \( V_{FAR-FIELD} \) are inversely proportional. The question that remains is, why not maximize \( d \) and minimize \( AM \) (and \( NB \))? The answer is a trade-off in spatial resolution of post-measurement processing. This analysis uses a specific and ideal planar contrast that extends infinitely into the horizontal plane. On the other hand, if the geologic setting is more finite (e.g. a 1m diameter boulder that moves with respect the surface), the finite anomaly may go unseen by the electrode array if \( d \) is too large or \( AM / NB \) is too small.

A limitation of the models presented in Figure 6.1 rests in their lack of electrical noise incorporation. In a field setting, electrical noise will be present and can affect the ability of an electrode array to detect differences like the one shown in Figure 6.1. If the electrical noise is greater than the theoretical noise free measurement of \( \Delta V_{MN} \) then the planar difference remains undetected due to a signal to noise ratio less than unity. The theoretical \( \Delta V_{MN} \) must exceed the noise threshold before \( V_{FAR-FIELD} \) can be determined. Electrical noise will be incorporated into the following analysis of electrical resistivity applied to the tunnel boring machine in order analyze how geometry of the tunnel, tunnel boring machine, and the electrode array can influence the ability to detect incoming changes ahead of the tunnel face.

### 4.2 Tunnel Boring Machine Environment and Geometric Variables

A tunnel is comprised of a hollow cylinder of diameter \( D \), which is located at a cover depth \( C \) below the earth’s surface (Figure 6.3). The TBM structure is located at the closed end of the cylinder and is comprised of both the cutterhead and the shield. To the left of the TBM structure is a lining constructed of either shotcrete, cast-in-place concrete or precast concrete.
segments. Unlined tunnels are not considered here. Air fills the inside of the tunnel at atmospheric pressure.

Figure 6.3 illustrates a simplified tunneling environment where the TBM makes perfect physical contact with the surrounding virgin formation. In reality, complexities are present that alter the perfect contact case shown and could be generated by the introduction of cutting tools and additives used to aid in the excavation. These complexities are not discussed in this Chapter, but are detailed in Chapter 5.

![Figure 6.3: TBM tunneling environment with dimensions and material properties](image)

This study analyzes the effects of geometry for two unique electrode arrays (Figure 6.4.), originally presented in Chapter 5 as integral mode and scan mode. In Chapter 5, the geometry of the electrode array is held constant as a change advances toward the TBM. In this chapter, the effects of a changing electrode geometry are presented. The prominent geometric variables are illustrated in Figure 6.4. These include:

- The cover depth $C$ (m); $C$ is ranged from 20m (near surface) to 400m below the surface
- The TBM diameter $D$ (m); $D$ is ranged from 2m (micro-TBM) to 15m (large transit TBM)
- The separation between the separation between electrodes A and M, $\overline{AM}$; for integral mode, $\overline{AM}$ is ranged between 1m and 50m; for scan mode, $\overline{AM}$ is ranged between 1m and 9m
The separation between the separation between electrodes N and B, $\overline{NB}$ is ranged between 1m and 225m.

The separation between the separation between electrodes A and B, $d$; $d$ is ranged between 11m and 200m.

As each of these variable is parametrically tested, the other variables are held constant in order to isolate the variable of interest. The base dimensions for the model will be set equivalent to those from the previous integral mode and scan mode configurations presented in Chapter 5.

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**Figure 6.4: TBM electrical resistivity electrode configurations (a) integral mode (b) scan mode**

### 6.3 Finite Element Model Set-Up

Computational finite element modeling is used to evaluate the ability of an electrical resistivity array to predict a change (geologic and pipe) ahead of the TBM. Models were constructed and run using COMSOL Multiphysics with the same specifications as defined in Chapter 4. The model space is shown here again in Figure 6.5.

Figure 6.5 illustrates the COMSOL model space. Figure 6.5(a) shows the front and center of a tunnel boring machine located in the center $(x,y,z = 0,0,0)$ of a 500m cube. The TBM in Figure 6.5 does not reflect a specific machine type (hard rock, EPB or slurry). The reader should note that the influence of the interface region was analyzed in Chapter 4 and so this
chapter does not incorporate it into the simulations. For these simulations, the TBM is assumed to make perfect electrical contact with the surrounding formation, $\sigma_1$.

![Figure 6.5: Finite element domain and dimensions (a) with TBM and refined element mesh Area of Interest (AOI), (b) close-up cross section of TBM with cutting tools](image)

While holding the geometry of the tunnel, TBM, and electrode geometry constant, the ability for electrical resistivity to predict incoming changes (vertical inclusion, boulder, pipe etc.) was analyzed in Chapters 4 and 5. In Figure 6.6, a vertical planar difference is shown at a distance of $x_D$ in front of the TBM for the condition where $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m. As the TBM excavates from left to right ($\sigma_1$), it will approach a change in ground conditions ($\sigma_2$). For example, $\sigma_1$ and $\sigma_2$ could represent a saturated sand and a saturated clay, respectively. The analysis performed here will investigate the influence of each geometric variable introduced in Figure 6.4 on the ability of the electrode array to predict the changing ground condition presented in Figure 6.6.

Electrical current is injected/retrieved at a magnitude of 15 Amps and is consistent with the modeling performed in Chapters 4 and 5, and the analysis for maximum level of safe current injection performed in Appendix B.
Figure 6.6: Vertical planar difference at a distance $x_D$ in front of TBM for $\sigma_1 = 10^{-2}$ S/m and $\sigma_2 = 10^{-1}$ S/m

6.4 Results and Analysis

The results for the finite element study are presented in this section, where each of the geometric variable presented in Figure 6.4 are individually evaluated while holding the others constant. Each of the variables is given a reasonable range and tested incrementally throughout the range by simulating the TBM advance toward the vertical planar difference as shown in Figure 6.6.

Consistent with the findings from previous chapters, the curves of $\Delta V$ becomes increasingly negative for decreasing values in $x_D$ (the observed average electrical conductivity is increased as the TBM moves towards $\sigma_2$ and so, Ohm’s law dictates that the measured electrical potential must decrease). In the field, it is expected that some electrical noise exists from a variety of sources (e.g. electrical field of the earth, seismo-electric affects). In an attempt to make these simulations more realistic, a constant noise threshold is defined at -1V. Under this amplitude, the electrode array cannot detect the change in ground conditions because of a signal to noise ratio less than one. Outside of this amplitude, $\Delta V$ exceeds the noise amplitude, and therefore, can be detected by the electrode array. The point at which $\Delta V$ exceeds the noise threshold is called the look-ahead distance $x_L$ ($x_L = x_D @ \Delta V = -1V$). The look-ahead distance is plotted in this section in order understand the behavior of each geometric variable.
Figure 6.7 shows curves of $\Delta V$ vs. $x_D$ for various values in the diameter of the TBM and both integral (Figure 6.7a) and scan mode (Figure 6.7b). For each of the different diameter simulations, a different look-ahead distance is achieved when the electrical noise threshold is overcome. The inlaid plot confirms a relationship as the TBM diameter decreases, the look-ahead distance non-linearly increases. For example, the Figure 6.7(a) inlaid plot shows a look-ahead distance of approximately 1.2 TBM diameters for $D = 15m$ ($x_L \approx 18m$). In comparison, $D = 2m$ gives a look-ahead distance of approximately 69 TBM diameters ($x_L \approx 137m$).

The contour plots in Figure 6.8 shows current density contours (mA/m$^2$) for integral mode when the planar difference is at $V_{FAR-FIELD}$. The contour plots show that as the TBM diameter is increased, the spread of current density around the TBM is reduced. For example, for $D = 2m$, the 14mA/m$^2$ contour is seen at just over $x = 8m$ in front of the TBM. In comparison, when $D = 15m$, the 14mA/m$^2$ contour only reaches $x = 1m$ in front of the TBM. This result is due to the influence of the metallic TBM introduced into each of the models. Since the TBM shield and cutterhead are both given a thickness of 0.5m for all models, as the TBM diameter of the TBM increases the volume of metal also increases. Metal is highly conductive compared to the earth and so it attracts the electrical current introduced into the model.

Comparing the inlaid plots of $D$ vs. look-ahead distance plots for integral mode and scan mode, Figure 6.7(b) shows that there is a slight advantage in using current injection from an individual cutting tool as opposed to using the entire TBM for predicting the vertical planar difference. For example, the subplot in Figure 6.7(a) the look-ahead distance for $D = 15m$ is approximately 18m. In contrast the subplot in Figure 6.7(b) yields a look-ahead distance for $D = 15m$ of approximately 20 meters. The comparison of the current density contour plots from Figures 6.8 and 6.9 shows why scan mode has a slight advantage over integral mode for prediction of the vertical planar difference.
Figure 6.7: Measured $\Delta V$ for incoming vertical planar difference as a function of TBM diameter, $D$ (a) integral mode, (b) scan mode

The smaller volume cutting tool allows from larger current densities observed in its vicinity (i.e., smaller volume for similar current magnitude of 15A). Recall from Chapter 5 that this behavior is highly advantageous for detecting smaller anomalies and will yield significantly increased look-ahead distances compared to integral mode.

For reference, in integral mode, if all electrical current flows through the TBM ($D = 10$m) and into the earth, then the current densities seen just outside the TBM would be approximately 38 mA/m². In scan mode, if all electrical current flows through the cutting tool and into the earth, then the current densities seen just outside the cutting tool would be approximately 57,000 mA/m². Much larger current densities around the cutting tool for scan mode mean that larger measurements in $\Delta V$ can be realized when an anomaly comes within the vicinity of the current source.
Figure 6.8: Electrical current density (mA/m$^2$) contour plot for a vertical cross section of tunnel boring machine in $x$(m), $z$(m) ($y=0$m) space; integral mode
Figure 6.9: Electrical current density (mA/m²) contour plot for a vertical cross section of tunnel boring machine in x(m), z(m) (y = 0m) space; scan mode.
Figure 6.10 shows a relationship between the tunnel cover and the look-ahead distance by similarly plotting $\Delta V$ vs. $x_D$ for various values of tunnel cover depth. As opposed to the models presented previously in Chapters 4 and 5, here the TBM is positioned at shallower depths in order to understand the influence that the ground surface plays on the ability to detect changes ahead of the tunnel face. Figure 6.10(a) shows that integral mode achieves an increased look-ahead distance from the proximity of the ground surface.

This can be explained by the equation for calculating current density in an infinite half space from a point source discussed in detail in Chapter 2. Recall that this equation defines that current will radiate in a spherical manner away from the source due to the ‘$r^2$’ in the denominator of the equation. Due to the close proximity of the ground surface, the flow of electrical current is restricted above the tunnel crown as it is not able to equally radiate current in all directions at shallower depths. This restriction is current flow above the tunnel ‘focuses’ the current to flow in other directions, including the desired $x$-direction.

At sufficiently large depths (here $C = 100m$), the ground surface has no impact on the flow of electrical current and so there is no effect on the look-ahead distance as electrical
current is able to freely radiate in all directions. This behavior can be visually explained in Figure 6.11, which shows current flows lines using integral mode for different values of $C$. Observe that as the tunnel cover is moved closer to the ground surface, the current flow lines are focused directly in front of the TBM before they circle back to the current sink.

For scan mode presented in Figure 6.10(b) the influence of the ground surface is less straightforward. In the subplot, it can be seen that the look-ahead distance fluctuates as the tunnel cover increases until a cover of approximately 250m. The fluctuation is not well understood, but is expected to be a product of the asymmetry of the current source location relative to the TBM. At the value of $C = 250$m, the ground surface no longer influences the look-ahead distance and remains relatively constant at 32m. Coincidentally, the location of the current sink is 250m back from the current source (cutting tool). This phenomenon be explained and will be discussed in later in this chapter the geometric variable $d$ is analyzed.

Figure 6.12 show plots for $\Delta V$ vs. $x_D$ when $\overline{AM}$ is varied. In subplots, it can be seen that the look-ahead distance is inversely proportional to $\overline{AM}$. This result is analogous to the analysis performed in the beginning of this chapter and can be verified in Figure 6.13, which shows lines of equipotential around the current source for both integral and scan mode. Subfigures 6.13(b) and 6.13(d) are zoomed-in images of subfigures 6.13(a) and 6.13(c), respectively.

In either integral or scan mode, the gradient of equipotential (also called the electric field, $E = V/m$), is stronger closer to the source. Each equipotential line shows a 5V drop/increase in electrical potential relative to the equipotential line on either side of it. Equipotential lines located closer to the source are more closely spaced than lines further away from the source, thereby representing a stronger and weaker electrical field, respectively. If $M$ is positioned closer to the source, then it will measure larger changes in potential because the electric field is stronger. At the other end of the scale, if $M$ is located very far from the source (i.e., $\overline{AM} \to \infty$), then it will
measure relatively zero change in potential as it is too far away from the any current density to enact a measurable change in potential according to Ohm’s law.

Figure 6.11: Electrical current flow lines from current source (cutting tool) to current sink for various cover depths (a) $C = 20m$, (b) $C = 60m$, (c) $C = 100m$, (d) $C = 200m$; integral mode

Figure 6.14 shows the influence of the $\overline{NB}$ on the look-ahead distance and the result is comparable to the discussion given for $\overline{AM}$. As N moves further from B, the gradient in electrical potential is decreased and so the sensitivity ($\Delta V$) to changes is also decreased (Figure 6.15). The reader should note, however, that the results presented here are ideal and in reality the earth is not made of a two homogeneous vertical layers. Many anomalies, and even changes within similar material (i.e., regions of increased fracturing within rock), exist all around the tunnel. Since the purpose of these methods is to detect changes ahead of the tunnel face (as opposed to on the side of the tunnel), it may be advantageous to separate N from B
adequately as to measure a relatively consistent potential at N. Therefore, $\Delta V$ would be more influenced by changes in the potential measured at M instead of changes at both M and N (a change in potential at N could result in a false positive ahead of the TBM). In this study, B and N are positioned at opposite ends of the tunnel (crown and invert), but further research should investigate the effects of anomalies present at the sides of the tunnel on the prediction ahead of the tunnel face.

![Figure 6.12](image)

**Figure 6.12: Measured $\Delta V$ for incoming vertical planar difference as a function of the source/potential electrode spacing, $\overline{AM}$ (a) integral mode, (b) scan mode**

Again, the reader should note that by increasing $d$, the current density increases in front of the tunnel face but also around the tunnel. This may cause a false positive by detecting changes around tunnel instead of ahead of the tunnel face. This result was discussed in Chapter 5 for a diagonal change ahead of the TBM. When the angle of the change was very small (e.g., $\theta = 5^\circ$), a strong measurement in $\Delta V$ was recorded even though the TBM was very far away ($x_D = 100$’s of meters) from the change along the alignment. This result is because current flows in all directions and so M and N had detected the change below the tunnel invert.
This result is perhaps a major flaw in these methods and attempts at focusing electrical current should be made.

Figure 6.13: Contour plot of select equipotential lines shown in proximity to current source (A) for vertical cross section (x(m) vs. z(m)) at y = 0m. (a) zoomed-out contour plot of integral mode, (b) zoomed-in contour plot for integral mode, (c) zoomed-out contour plot for electrode array for scan mode, (d) zoomed-in contour plot for scan mode
Aside from the diameter of TBM, the most influential geometric variable presented in this study is the separation of the A and B, called ‘d’. Figure 6.16 shows the results for $\Delta V$ vs. $x_0$ as $d$ is changed. For either integral or scan mode, the look-ahead distance is proportional to $d$ until some value of $d$ when the look-ahead distance sees no advantage to in increasing $d$.

An interesting result from the subplots shows the value of $d > 200$m is needed to achieve a relatively constant look-ahead distance. In either integral or scan mode, a constant look-ahead distance is achieved at $d = 245$m, which is coincidentally the cover depth of the tunnel. Recall from Chapter 2 that current radiates evenly in a homogeneous medium. After the current escapes away from the TBM it attempts to spherically fill the volume. A visual representation of the current flow lines (Figures 6.17 and 6.18) show why this is the case. The current flow lines shown in Figures 6.17 and 6.18 show that for each value of $d$ (i.e., $d = 15, 50, 100, 200$m), that the current wants to fill a relative spherical space. As such, when $d$ is increased, the radius in which current propagates from the source (or to the sink) is also increased, thereby increasing current propagation in front of the TBM in the $x$-direction.
Figure 6.15: Contour plot of select equipotential lines shown in proximity to current sink (B) for vertical cross section (x(m) vs. z(m)) at y = 0m. (a) zoomed-out contour plot of integral mode, (b) zoomed-in contour plot for integral mode, (c) zoomed-out contour plot for electrode array for scan mode, (d) zoomed-in contour plot for scan mode.
Figure 6.16: Measured $\Delta V$ for incoming vertical planar difference as a function of the source/sink separation, $d$ (a) integral mode (b) scan mode

Figure 6.17: Electrical current flow lines from current source (cutting tool) to current sink for various source/sink separation distances (a) $d = 15m$, (b) $d = 50m$, (c) $d = 100m$, (d) $d = 200m$; integral mode
Figure 6.18: Electrical current flow lines from current source (cutting tool) to current sink for various source/sink separation distances (a) $d = 15\text{m}$, (b) $d = 50\text{m}$, (c) $d = 100\text{m}$, (d) $d = 200\text{m}$; scan mode

6.5 Conclusions

This chapter presents finite element results from a three dimensional study on electrical resistivity methods applied to the TBM tunneling environment in order to investigate how different geometric variables associated to both the TBM/tunnel environment and the electrode array can influence the ability to predict changes ahead of the tunnel face. This analysis used a simple vertical planar difference in geology to simulate a change ahead of the TBM for the condition where the TBM is surrounded by $\sigma_1 = 10^{-2} \text{ S/m}$ with an incoming planar difference of $\sigma_2 = 10^{-1} \text{ S/m}$. Several geometric variables were ranged in order to determine their influence for two different electrode arrays called integral mode and scan mode, which aim to simulate their commercial counterparts from the BEAM and BEAM4 systems:
• The TBM diameter \( D \) (m)
• The cover depth \( C \) (m) of the tunnel alignment
• The separation between the separation between electrodes A and M, \( \overline{AM} \)
• The separation between the separation between electrodes N and B, \( \overline{NB} \)
• The separation between the separation between electrodes A and B, \( d \)

The diameter of the TBM, \( D \) (m) was ranged from 2m (micro-TBM) to 15m. It was found that as the diameter of the TBM was increased, the look-ahead distance was decreased non-linearly due to an increasing influence of the TBM. Since the TBM is made of metal, it is highly conductive compared to earth and so it acts to draw current back from the tunnel face.

The cover depth of the tunnel alignment, \( C \) (m), was ranged between 20m and 400m. The conclusions drawn for integral mode and scan mode were slightly different from one another. In integral mode, as \( C \) decreased, the look-ahead distance increased due to an indirect current focusing effect from the proximity of the ground surface. Since current will flow in a spherical manner in a homogenous medium, the ground surface forces current in front of the TBM. Scan mode showed inconclusive results for the influence of the ground surface due to fluctuation of the look-ahead distance vs. \( C \). For both integral mode and scan mode, a constant look-ahead distance was achieved when \( C \) became sufficiently large. For integral mode, a value of \( C \approx 100m \) showed an equilibrium condition where the look-ahead distance was not influenced by any increase in \( C \). For scan mode, this equilibrium condition was achieved at \( C \approx 240 \).

The electrode array geometric variables \( \overline{AM} \) and \( \overline{NB} \) showed very similar behavior over their respective ranges. The modeling showed that as M (or N) moves away from A (or B), the potential measuring electrode moves toward a weaker electric field. Therefore, any change in the electric field will be recorded as a smaller \( \Delta V \). In general, placing M (or N) as close to A (or B) as possible will increase the ability to predict ahead of the machine. A consequence to this, however, will be a decrease in spatial resolution. In order to detect finite anomalies at the
tunnel face, a number of electrodes at various radii in order to resolve small changes (e.g., boulders, lenses) ahead of the TBM.

The source separation distance, \( d \) (m), was varied between 15m and 250m. The model results showed that as \( d \) is increased, the look-ahead distance was also increased as it allowed for a larger distribution of electrical current density, particularly in front of the TBM. The reader should note, however, that these models present very simple cases for ground conditions. When the ground conditions are more heterogeneous, an increase in \( d \) will lead to resolution decrease and may provide a false positive as changes will occur around the TBM in addition to direct in front of the machine. Electrical current focusing methods are highly advantageous here in order to increase the look-ahead distance but only for changed directly in front of the TBM.
CHAPTER 7
CONCLUSIONS, RESEARCH LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Summary

The research presented throughout this study evaluated the application of well-established electrical resistivity theory to the TBM tunneling environment in order to predict changes ahead of the machine. Using experimental and computational finite element methods, the studies presented in this dissertation evaluated and identified several factors that contribute to the relative success of predicting changes ahead of the tunnel face. The results of the studies showed that, in general, electrical resistivity can be applied to the TBM tunneling environment to predict changes up to 70 TBM diameters for micro-TBMs and up to 5 TBM diameters for full size TBMs. The conclusions from each study are presented in the following.

7.2 Laboratory Scaled Model Testing for the Prediction of a Metal Pipe or Rod Ahead of the Tunnel Boring Machine Using Electrical Resistivity Theory

The following conclusions can be made from the results from Chapter 3:

An experimental study was performed using a scaled TBM model with integrated electrical resistivity electrodes. Two unique electrode configurations were used and made several spatial measurements of voltage at the tunnel face as the TBM advanced toward a metallic pipe or rod of known size and location in a tank full of saturated sand.

The following conclusions can be drawn from the results presented in this chapter:

- For the detection of a pipe that is laterally centered in the tunnel face, integral mode and scan mode provide nearly identical ability to detect the pipe when electrical current is injected symmetrically (either full TBM or centered on the cutterhead through a cutting tool).
Either integral mode or scan mode are capable of identifying a conductive difference ahead of the TBM by almost three TBM diameters.

The ability to uniquely identify the presence of a pipe or rod is not conclusive, however, the data suggests that, in comparison of these two configurations, integral mode was able to resolve a relatively narrow conductive difference that was centered in the tunnel face within 1.5 TBM diameters.

When the experimental data was compared to the finite element results, both show that the electrode array has predicted an incoming conductive difference ahead of the TBM. However, the computational results do show correlate strongly with experimental curves with respect to general shape, particularly how computational models do not reproduce ideal, smooth exponential curves.

By assuming an inaccurate experimental evaluation of the conductivity for the saturated sand within the tank of \( \sigma = 0.011 \, \text{S/m} \), further computational modeling shows that perhaps the experimental compaction procedure does not uniformly densify the saturated sand versus depth. A slight increase in sand density with depth could explain a gradient in electrical conductivity and therefore more closely resemble experimental conductions.

These experimental simulations do not suggest that integral mode is better than scan mode for the detection of the metallic pipe/rod. In these experiments, the spatial resolution of data is extremely lacking with only eight or nine points of information throughout the entire tunnel face. In the field, it is highly recommended that for the detection of smaller anomalies in the face, dozens of electrodes should be employed on the cutterhead to increase the spatial resolution of data.

7.3 Electrical Influence of the Interface Region

The following conclusions can be made from the results from Chapter 4:
This chapter presents finite element results from a three dimensional study on electrical resistivity methods applied to the TBM tunneling environment. This study focuses on identifying the electrical influence of a volume that interfaces the TBM to the virgin formation, called the interface region. There is a degree of uncertainty regarding the interface region regarding its electrical conductivity and geometry and so this study considers a range in each. Six electrode arrays are considered that are unique to TBM-integrated-electrical resistivity in an attempt to understand the influence of the interface region to a number of possible implementations in the field. The following conclusions can be drawn from the findings:

- For all six electrode configurations, significant current densities (>1mA/m²) can be observed out to 30 m ahead of the 10 m diameter cutting face when the TBM is perfectly coupled to formation (i.e. no interface region). When the interface region is introduced, it has a varying amount of influence on the ability of current density to propagate in front of the TBM. The influence of the interface region is dependent upon the method of the current injection (i.e. full TBM body or isolated cutting tool) as well as the TBM type (i.e. hard rock, EPB and slurry).

- Electrode configurations that inject current from the entire TBM body (cutterhead and shield) are negatively influenced by the presence of the interface region because it isolates the injection electrode from the formation. Current density propagation distance is decreased by as much as 30% depending upon the configuration of the interface region. The exception to this is when the interface region consists only of the annulus, in which case current is focused through the cutterhead and current density propagation is increased by approximately 20%.

- Electrode configurations that inject current from a single isolated cutting tool are positively influenced by the interface region where current density propagation is increased by approximately 20%. The best case scenario for these electrode configurations is given when the TBM is completely encapsulated by the interface
region, effectively shielding the large metal structure from the formation. In contrast to full TBM body injection, cutting tool injection demonstrates less of a range in influence to the interface region.

- Hard rock and EPB tunneling conditions offer identical observations for both current density propagation ahead of the TBM as well as $\Delta V_{MN}$ measurements taken for an incoming vertical planar difference.
- For slurry tunneling, the interface region has near zero influence on either current propagation ahead of the TBM or $\Delta V_{MN}$ measurements taken for an incoming vertical planar difference. This result is advantageous as the interface region is not a variable in electrical resistivity analysis throughout the excavation of the tunnel.
- Electrode arrays that position a current sink on the surface, in front of the TBM, show two regions of sensitivity due to the concentration of current density around the sink. In the field, these electrode arrays may be infeasible to implement and this result may provide a false positive detection of a change ahead of the cutting face.
- Electrical resistivity is more sensitive to an incoming vertical planar difference that is more conductive than for one that is more resistive than the formation surrounding the TBM.

Simulations suggest that TBM-integrated-electrical resistivity can detect a planar difference in geology up to five diameters in front of the TBM. This look-ahead distance is subject to change for other types of geologic/man-made differences ahead of the TBM due to their contrasting size, location and electrical properties.

### 7.4 Prediction of Geologic Changes or a Metal Pipe Ahead of the Tunnel Boring Machine Using Electrical Resistivity Theory

The following conclusions can be made from the results from Chapter 5:
This chapter presents finite element results from a three dimensional study on electrical resistivity methods applied to the TBM tunneling environment in order to detect various geologic differences or a metal pipe in front of the TBM. A 10m diameter TBM was placed in a homogeneous condition $\sigma_1 = 10^{-2}$ S/m with a conductive change placed in front of it at a distance of $x_D$ with the condition $\sigma_2 = 10^{-1}$. Various changes were considered including a/n a) vertical planar difference, b) vertical planar inclusion, c) horizontal seam, d) diagonal planar difference, d) lens, e) spherical boulder, f) metallic pipe. Two different electrode configurations were simulated called integral mode and scan mode and are modeled similar to their commercial counterparts from the BEAM and BEAM4 electrical resistivity systems. The following conclusions can be drawn from the study:

- The look-ahead distance is proportional to the volume of the change ahead of the TBM. For example, a vertical planar difference can be predicted further ahead of the TBM than for a vertical planar inclusion.
- In general, scan mode is more successful at predicting a change ahead of the TBM than integral mode.
- Scan mode can predict finite anomalies ahead of the TBM because of a significant increase is spatial resolution of voltage measurement at the tunnel face. If multiple cutting tools are used for potential measurement, $M$, at various radii, as the cutterhead rotates, the electrode array will scan the tunnel face for anomalies present directly in front of the TBM.
- The ability to uniquely characterize changes ahead of the TBM may be possible through the process of inversion. The contour plots at the tunnel face for the prediction of a pipe versus a lens at the crown showed significant differences in the distribution of $\Delta V$ due to the conductivity contrast of the change.
7.5 Electrical Influence of the TBM Tunnel Environment and Electrode Geometry

The following conclusions can be made from the results from Chapter 6:

This chapter presents finite element results from a three dimensional study on electrical resistivity methods applied to the TBM tunneling environment in order to investigate how different geometric variables associated to both the TBM/tunnel environment and the electrode array can influence the ability to predict changes ahead of the tunnel face. This analysis used a simple vertical planar difference in geology to simulate a change ahead of the TBM for the condition where the TBM is surrounded by $\sigma_1 = 10^{-2} \text{ S/m}$ with an incoming planar difference of $\sigma_2 = 10^{-1} \text{ S/m}$. Several geometric variables were ranged in order to determine their influence for two different electrode arrays called integral mode and scan mode, which aim to simulate their commercial counterparts from the BEAM and BEAM4 systems:

- The TBM diameter $D$ (m)
- The cover depth $C$ (m) of the tunnel alignment
- The separation between the separation between electrodes A and M, $\overline{AM}$
- The separation between the separation between electrodes N and B, $\overline{NB}$
- The separation between the separation between electrodes A and B, $d$

The diameter of the TBM, $D$(m) was ranged from 2m (micro-TBM) to 15m. It was found that as the diameter of the TBM was increased, the look-ahead distance was decreased non-linearly due to an increasing influence of the TBM. Since the TBM is made of metal, it is highly conductive compared to earth and so it acts to draw current back from the tunnel face.

The cover depth of the tunnel alignment, $C$(m), was ranged between 20m and 400m. The conclusions drawn for integral mode and scan mode were slightly different from one another. In integral mode, as $C$ decreased, the look-ahead distance increased due to an indirect current focusing effect from the proximity of the ground surface. Since current will flow in a spherical manner in a homogenous medium, the ground surface forces current in front of the
TBM. Scan mode showed inconclusive results for the influence of the ground surface due to fluctuation of the look-ahead distance vs. \( C \). For both integral mode and scan mode, a constant look-ahead distance was achieved when \( C \) became sufficiently large. For integral mode, a value of \( C \approx 100 \text{m} \) showed an equilibrium condition where the look-ahead distance was not influenced by any increase in \( C \). For scan mode, this equilibrium condition was achieved at \( C \approx 240 \).

The electrode array geometric variables \( \overline{AM} \) and \( \overline{NB} \) showed very similar behavior over their respective ranges. The modeling showed that as \( M \) (or \( N \)) moves away from \( A \) (or \( B \)), the potential measuring electrode moves toward a weaker electric field. Therefore, any change in the electric field will be recorded as a smaller \( \Delta V \). In general, placing a \( M \) (or \( N \)) as close to \( A \) (or \( B \)) as possible will increase the ability to predict ahead of the machine. A consequence to this, however, will be a decrease in spatial resolution. In order to detect finite anomalies at the tunnel face, a number of electrodes at various radii in order to resolve small changes (e.g., boulders, lenses) ahead of the TBM.

The source separation distance, \( d(\text{m}) \), was varied between 15m and 250m. The model results showed that as \( d \) is increased, the look-ahead distance was also increased as it allowed for a larger distribution of electrical current density, particularly in front of the TBM. The reader should note, however, that these models present very simple cases for ground conditions. When the ground conditions are more heterogeneous, an increase in \( d \) will lead to resolution decrease and may provide a false positive as changes will occur around the TBM in addition to direct in front of the machine. Electrical current focusing methods are highly advantageous here in order to increase the look-ahead distance but only for changed directly in front of the TBM.

### 7.6 Research Conclusions

This study has investigated a number of aspects pertaining to what influences the ability to predict changes ahead of the TBM. Conclusions were drawn for each of the chapters.
presented in this dissertation, but a few common conclusions can be generally drawn for what was learned throughout this study.

The research presented in this dissertation shows the electrical resistivity is capable of detecting most changes ahead of the TBM, even in situation of very high electrical noise (electrical noise given as magnitude of 1 Volt in Chapter 5). Under certain conditions (i.e., smaller TBM diameter, low cover depth, slurry TBM), electrical resistivity is capable of becoming a strong tool for detection of unanticipated changes and increasing ground truth ahead of the TBM during excavation. This dissertation identified a number of factors than can influence the relative success of electrical resistivity in the TBM tunnel environment. However, the quantitative analysis of how each of these factors can influence electrically resistivity is not quite as important as simply knowing that these factors exist. Since geophysical inversion is a delicate and complicated process, rigorous and well-tuned models that reflect realistic tunnel conditions (e.g., interface region, electrode geometry) are critical for accurate prediction ahead of the face. Deviations from reality may provide a result that is either inaccurate or false altogether. This dissertation has attempted to cover several of these factors, but even still takes on assumptions that deviate from realistic field conditions.

Beyond accuracy, spatial resolution can be essential for prediction of more finite anomalies. Some electrode configurations that implemented an electrically insulated cutting tool, called scan mode in Chapters 5 and 6, showed the need for measuring relatively discrete point on the face of the cutterhead. Without the implementation of cutting tools or other electrodes on the cutterhead as points of potential measurement, finite anomalies such as boulders and lenses could go undetected.

7.7 Research Limitations and Future Research Recommendations

Recent research has demonstrated that the non-uniqueness of electrical resistivity to lithological type can be improved by characterizing a material's complex conductivity over a broad range in frequencies with induced polarization (IP) methods [3], [4], [5], [40], [48], [66].
Even though IP methods were outside of the scope of this research, an evaluation of IP methods to the TBM tunneling environment should be performed for further research.

The research presented in this dissertation studied the fundamentals behind the application of electrical resistivity to the TBM tunneling environment by studying measured voltages and visualizing current density and flow paths. For these methods to truly be successful in a field setting, this application cannot rely solely on voltage measurements and contour plots. Advancements in computational speed and power allow for rigorous and detailed inversion algorithms [68] capable of mapping a three dimensional map of electrical conductivity in front of and around the TBM from points of measurement at the tunnel face. Even for the most powerful inversion algorithms, the TBM tunneling environment is extremely complex and varies in three dimensions. The history of inversion and its process is very complex and lengthy. For more information on the inversion and computational modeling processes, the reader is encouraged to reference extended literature (e.g., [7], [11], [69]).

Noise from stray or ambient electrical currents is of great concern to the ability to predict ahead of the tunnel face. This research employed various threshold values of electrical noise in Chapters 5 and 6, and even suggested a measurement depending equation in Chapter 4 for determining maximum levels of electrical noise. Yet, any of these suggestions are inherently arbitrary and the actual level of noise is likely transient and site specific. Further research should implement these methods to passively measure electrical noise in a real TBM field setting and compare to recorded DCR measurements.

One of the largest limitations of these research was the inability to extend the knowledge for field implementation. A field implementation is critical, not only for identifying electrical noise levels or feasible implementation strategies, but also to understand how highly complex ground conditions can affect the ability of detecting larger features ahead of the TBM.
REFERENCES


[42] Revil, A., K. Koch, and K. Holliger (2012a), Is it the grain size or the characteristic pore size that controls the induced polarization relaxation time of clean sands and sandstones? Water Resour. Res.


APPENDIX A

DESIGN AND IMPLEMENTATION CONSIDERATIONS FOR FIELD SCALE ELECTRODE ARRAY

A.1 The Tunnel Boring Machine

In general, a TBM is comprised of a cutterhead, cutting tools (for breaking apart virgin earth), a tail shield and internal workings (e.g., main bearing, trailing gear, thrust jacks (thrust ram), tunnel lining erector). Behind the shield, a lining is constructed to carry the load of the earth and prevent deformations around the opening of the tunnel and settlement at the ground surface. A generic schematic of a TBM is shown in Figure A.1 [70]

![Figure A-1: Schematic of a generic TBM from Pennington [70]](image)

The cutterhead is allowed to independently rotate from the rest of the machine such that the cutting tools (mounted on the face of the cutterhead) crush and break apart the soil/rock in front of the machine. The plane at which the cutting tools make contact with the virgin earth is
called the tunnel face. As soil and rock is broken off of the tunnel face, it is transported through various methods through the cutterhead and through the tunnel to be hauled away from the site. Concurrently, the machine is thrusted/advanced forward always applying stress as to mitigate collapse of the tunnel face and/or settlement of the surface above the tunnel. This is especially critical in urban environments where tolerances for settlement are very low (on the order of a couple centimeters or less).

As detailed in Chapter 4 of this dissertation that analyzed the effects of the so-called interface region, the interface region is theorized to be created by an over excavated annulus by angled cutting tools on the perimeter of the cutterhead. The annulus is intentionally created so that the TBM is not squeezed by the ground, preventing it from advancing forward. An illustration of the annulus is shown in Figure A.2, where the tail shield passes alongside the formation. A concrete liner is constructed inside of the tail shield to be even smaller in diameter than the TBM. Sealing brushes (covered in sealing fluid) seal the inside of the TBM from inflowing earth, water or grout that used to fill the annulus gap between the lining/TBM and the formation. This practice of an over excavation around the TBM is the main principle behind the inception of the interface region, which is the foundation of the analysis performed in Chapter 4.

![Figure A-2: Illustration of interaction between tail shield and concrete liner through sealing brushes for inflow prevention](image)

Manufacturers of cutting tools design proprietary shapes and sizes of that are made to be the most efficient for certain types of ground conditions. Rippers and scrappers (example of
a scraper in Figure A.3) are called drag tools because they are designed to drag along the
tunnel face as the cutterhead rotates. This acts to pull/break material off of the face. Drag tools
are typically used in soils that are more malleable and plastic such as soft ground conditions
(i.e., clays silts and sands). Although research aims for more high strength design and
materials, a significant disadvantage to these tools are that they are susceptible to damage,
particularly in mixed face conditions where a sudden change in ground conditions (e.g., soil to
rock) can easily shear tools off of the cutterhead.

In contrast to drag type tools, disc cutters (example of disc cutter in Figure A.4)
independently rotate on the cutterhead of the TBM. Disc cutters are used more for hard rock
conditions and can withstand stresses above 400 MPa to crush the rock as they apply stress to
the tunnel face. Discs are not ideal for soft ground conditions as they can become clogged in
high plasticity material and be rendered useless for further tunneling until cleaned. In a
significant number of modern tunnel excavations, ground conditions are mixed where both types
of tools are needed for efficient excavation.

TBMs have had applications in many fields such as waste/water transport, transportation
and mining, and therefore have seen a range in size depending upon the application. Micro-
TBMS uses most commonly for utilities and waste/water transport are typically less than a few
meters in diameter. Full size TBMs used in transportation systems have seen diameters of over
17m (e.g., Big Bertha - Seattle Alaskan Way Viaduct Replacement Program; Figure A.5).

In addition to the versatility of cutting tools for various ground conditions, different types
of TBMs have emerged over the years in order to combat complex geologies and mixed face
conditions. Three types of TBMs are identified for the purposes of this research and are
presented in the following.
Figure A-3: Examples of a scraper bolted to a spoke of a cutterhead

Figure A-4: Example of disc cutter (The Robbin’s Company)
TBM types are split in two groups:

(1) pressurized; typically used under the water table and in soft ground conditions where water inflows and face collapse are a concern.

(2) non-pressurized

There are two schools of thought for pressurized a tunnel face for soft ground conditions

1) slurry shield TBM

2) earth pressure balance (EPB) TBM.

Slurry shield TBMs (schematic shown in Figure A.6) use a bentonite slurry injected into what is called the mixing chamber of the TBM. Although it is not well-established, in theory, bentonite slurry flows through the cutterhead (between its spokes) and into a semi-permeable tunnel face to create a filter cake at the tunnel face. This is advantageous for two reasons:

1. The bentonite slurry filter cake acts as an impermeable layer at the cutterhead and so preventing excessive water inflows.
2. Bentonite acts as lubricant between the cutting tools and the tunnel face. Relative to the bentonite slurry, the virgin earth is rough and over time can wear cutting tools such they are no longer usable for excavation. At this point, cutting tools are necessarily replaced. The replacement process is long and dangerous. Although current research has aimed to create a robotic and autonomous replacement, the cost of new cutting tools and particularly the indirect costs associated with the downtime of the TBM are significant.

As soil/rock is broken from the tunnel face, it mixes with the slurry. Bits of soil/rock are denser than the slurry pumped into the mixing chamber and so they will naturally fall to the bottom of the tunnel (called the invert). Here the soil/rock/slurry mixture (called muck) is pumped out from the bottom of the mixing chamber. After the muck travels back through the tunnel, the slurry is separated from the soil/rock and reinjected into the mixing chamber. This process is repeated until the tunnel is fully excavated. The tunnel face is support through a controlled air bubble at the top of the mixing chamber.

Figure A-6: Slurry shield tunnel boring machine (TBM) illustration
EPB tunneling is another popular pressurized face TBM type which uses the excavated face material and thrust jacks to maintain stability of the tunnel face (Figure A.7). Foam conditioning agents (liquid surfactants and air) are injected both in front of the cutterhead and within the mixing chamber to create a plasticized ‘toothpaste-like’ material. A screw conveyor maintains pressure at the tunnel face by regulating the speed at which material passes through the screw. Combined with a thrusting force applied by the TBM on the erected tunnel lining, face stability can be maintained. The muck falls to a conveyor belt and it transported out of the tunnel. There exist a wide array of different conditioning agents and are proprietary to several companies worldwide that manufacture them. This research does not discuss the soil conditioning in great detail. Further information can be found in literature (e.g., [71]).

![Figure A-7: Earth pressure balance (EPB) tunnel boring machine (TBM) illustration](image)

Slurry shield and EPB TBMs offer a pressurized solution for maintaining stability of the tunnel face. In competent rock, additional support of the face is not necessary. During the excavation process, rock is capable of maintaining changing stress conditions and so can support itself in many cases.

For hard rock environments with competent rock and low water intrusion, excavation uses non-pressurized TBMs, also called open-mode TBM tunneling. In open mode, the tunnel face is open to atmospheric pressure and no shield is used. When the in-situ rock is expected to
be fractured and the tunnel is susceptible to water inflows, a shield (either single or double shield) is used to protect the machine and staff on board. In contrast to slurry shield and EPB pressurized tunnel where additives are injected and mix with the excavated material in front of the face, hard rock TBMs do not inject any additives and rely on ability of disc cutters to fracture the rock into bits that can be. More details on hard rock tunneling can be found in Maidl et al [72].

A.2 TBM Tunneling Environment Electrode Implementation

For an electrical resistivity array applied to the TBM tunneling environment, a single electrode may be comprised of any piece of metal that a) makes electrical contact to the medium of interest and b) that is electrically isolated from other metallic bodies. If both of these conditions are not achieved in the installation process, then measurements can become highly inaccurate at best and can be fatal in some applications. In the TBM tunneling environment, there are a few options for electrode implementation.

A.2.1 Tunnel Boring Machine Shield + Cutterhead as Electrode

A TBM can be generalized as a hollow cylinder that presides in the ground in front of the tunnel lining. Even though the cutterhead rotates independently from the tail shield, it is not expected that the two are completely electrically isolated. Therefore, in order to make the entire TBM an electrode, only a single electrical connection needs to be made to the machine. Making an electrical connection to the TBM through any electrically connected piece of metal is relatively simple, however, extreme caution should be taken when determining the location of the connection.

From an implementation standpoint, using the entire TBM as an electrode is comparatively simple to other choices but it presents an averaging problem that may yield lower spatial resolution of data particularly for larger diameter TBMs. If the implementation is feasible, smaller volume electrodes can provide higher spatial resolutions.
A.2.2 Cutting Tool as Electrode

Tunnel boring machines use an array of cutting tools (dozens of tools for a single machine) to help break, crush and rip apart the ground in front of the cutterhead. Since tunnels are constructed in a variety of ground conditions (e.g., hard rock, sands, clays) there exist a variety of different kinds of cutting tools. Figure A.8 shows a scraper tool that is bolted to the cutterhead.

![Scraper tool bolted to TBM cutterhead](image)

**Figure A-8: Scraper tool bolted to the TBM cutterhead**

Cutting tools are fastened to the cutterhead through bolts, wedges and welding. In all cases, a cutting tool is not originally electrically isolated from the TBM and so it must be retrofitted with electrical isolation in order to employ it as an electrode. This task is not trivial as replacing a metal connection with electrically insulating material (e.g., plastic, rubber) will undoubtedly weaken the structural connection between the cutting tool and the cutterhead. Moreover, even though it is not expected to be electrically isolation, the cutterhead does independently rotate with respect to the rest of the TBM and so an electrical slip ring is necessary in order to provide electrical current or measurement potential from a single cutting tool on the cutterhead. The electrical slip ring will briefly be presented later in this appendix.
Innovative materials have been developed over the years that focus on replacing metals with plastics for the reasons of electrical insulation in electronics and maintain material strength for very small parts. In particular a fiberglass-reinforced composite plastic called NEMA Grade G-11 was developed for small electrical circuit boards that is high in strength and extremely resistant to high temperatures. A 0.5” thick plate yields a compressive, tensile and shear strength of 63, 45, and 22ksi, respectively. These strengths are maintained up to 374 degrees Fahrenheit.

For a field scale implementation, a scraper tool (shown in Figure A.8) was modified in order to electrically isolate it from the cutterhead. Two insulating parts were designed to integrate into the modified scraper tool and ensure its structural connection to the cutterhead. These parts are illustrated in Figures A.9 and A.10 developed in Solidworks.

![Figure A-9: Solidworks three-dimensional design model of electrical insulating plastic plate for modified scraper tool (a) side section view, (b) isometric view, (c) top view](image)

Solidworks finite element simulations were run in order to test any loss in strength of the modified scraper tool with inclusion of the plastic parts. NEMA Grade G-11 plastic was defined
for the insulating parts in the model. Figure A.11 shows a three dimensional exploded view of the modified scraper tool to show how the pieces fit together.

![Figures A-10: Solidworks three-dimensional design model of electrical insulating plastic sleeve for modified scraper tool (a) side section view, (b) isometric view, (c) top view](image)

Solidworks simulator was used to analyze stress concentrations and strength reduction due to modification of the scraper tool and the addition of the G-11 parts. Figure A.12 shows the forces/stresses given to the cutting tool and were estimated based on typical values recorded.

Contour plots of the von Mises stress are shown in Figure A.13 for each of the corresponding cross sections. The unmodified cutting tool developed stress concentrations on the bottom right corner where it makes contact with the cutterhead. A maximum von Mises stress of 3.6 MPa is observed in this corner. When the scraper is modified and retrofitted with the G-11 plastic parts, stress concentrations can be observed to have developed at the plastic sleeves and travel to the bolted region for a maximum vonMises stress increase of 1.1 MPa (22% percent increase in the max vonMises stress of the unmodified scraper tool).
The model did not predict failure of any part of the modified scraper tool and held a factor of safety of nearly 50. However, given the significant costs associated with retrofitting these tools and replacement given potential failure, modification of cutting tools should be considered on a case by case basis. For the purposes on field implementation, a relatively small increase in stress did not signify significant risk of failure and so the design was sent for fabrication.

Figure A-11: Solidworks three-dimensional model exploded view of modified scraper tool showing designed insulting pieces (a) isometric view, (c) side cross section
Figure A-12: Estimated forces/stresses placed on the scraper tool in Solidworks Simulation (a) typical stability pressure of 500kPa, (b) frictional force based on stability pressure and typical coefficient of friction, (c) average torque on a single cutting tool based on measured torque of the full cutterhead.
The scraper tool in Figure A.8 was modified to accept the G-11 plastic pieces. The modified tool was assembled (Figures A.14(a) and A.14(b)) and installed onto the cutterhead (Figure A.14(c) and A.14(d)). The total cost of the modification for this cutting tool was approximately 400 dollars, however, in a larger quantity the cost per tool will significantly decrease.

After a tool has been either manufactured or retrofitted to be electrically isolated from the rest of the TBM, it can be installed onto the cutterhead. In order to connect this electrode to a central computing system or electrical resistivity meter, it must be given a physical electrical connection to the system/meter. This poses a problem given a rotating cutterhead and a non-rotating TBM body. In order to make an electrical connection to the electrode, implementation of what is called an electrical slip ring (or electrical rotary joint) is necessary.
Figure A-14: Photos of the modified cutting tool with retrofitted G-11 plastic insulating parts, (a) assembled scraper, (b) assembled scraper (view 2), (c) assembled scraper installed onto cutterhead, (d) assembled scraper installed onto cutterhead (view 2)

Figure A.15 shows an illustration of what a slip ring may look like. The figure shows three connections, but a slip ring may be designed for as many connections as is necessary. Each connection is run from the central unit or resistivity meter to a connection block shown. From the connection block a flinger-like metal rod touches a connection mount (or brush ring) that is banded around the rotor arm. As the rotor arm rotates with the cutterhead, an electrical connection can be maintained without the need for welding or mechanical connection.
2.2.3 Traditional Metal Stake as Electrode

In contrast to the above electrode types, all four electrodes used for a measurement of electrical resistivity do not need to be confined to the actual TBM. Chapter 2 covered some aspects of these stakes for implementation on a surface-based array. In the tunneling environment, stakes can be used as electrodes both on the surface of the earth above the tunnel or pushed through the tunnel lining and into the earth. The analysis performed in this dissertation evaluated both types.

Figure A.16 illustrates a proposed installation method for stakes through the tunnel lining such that they make contact with the earth. This installation is specific to a 10” thick concrete liner and a ½” bolt, but is generally applicable for any size liner.
Step 1: a 7/16 inch hole is to be drilled through a desired liner segment. This hole is undersized (for the eventual ½" stainless steel bolt) as to help mitigate water infiltration when the stake is fully installed. So that the segmental lining erector can lift the segment into place, this hole is to be drilled towards the outer perimeter of the desired segment. A small
recession is to be over cut in order to recess the eventual bolt head and avoid any aesthetic issues.

- Step 2: a ½ inch threaded stainless steel bolt is to be partially drilled into the concrete liner until it reaches the opposite side of the liner. This should be carried out before the segment is delivered to the inside of the tunnel for ease of installation and streamlining the stake installation process.

- Step 3: a concrete specific epoxy is to be brushed onto the visual threads of the partially threaded bolt. As the bolt continues to drill into the liner, the epoxy will work its way in between the bolt and liner to help mitigate water infiltration after the epoxy has dried. Note that this step requires semi-immediate fulfillment of step 4 depending upon the curing time of the epoxy.

- Step 4: The remaining portion of the stake should be drilled into the liner such that the bolt head is successfully recessed.
APPENDIX B

ELCTRICAL CURRENT LIMIT ANALYSIS

The look-ahead distance is directly proportional to the depth of current penetration, where the depth of current penetration is directly proportional to the magnitude of injected current, I (Amps). However, for safety considerations, it is essential to limit the magnitude of electrical current such that no individual is harmed on board the TBM via current leaked to the TBM in the case of an electrical short circuit. Based upon safety limits of current flow through a human being, an analysis on the total limit of available current is performed.

According to OSHA Title 29 Code of Federal Regulations (CFR) Part 1910.302 through 1910.308 – Design Safety Standards for Electrical Systems, the absolute limit of DC current which can pass through a human without physical damage is 3mA. This limit varies substantially when AC current is introduced in IP methods at different frequencies, but is only increased in these cases. When soaking wet (worst case scenario), OSHA estimates the average human electrical resistance to be on the order of 1,000 Ohms (1K Ohm).

A theoretical analysis of a TBM, earth, and human simple circuit, is performed. Figure B.1(a) shows the circuit diagram for three parallel legs of resistance. Current injected from a cutterhead electrode has three simple, parallel paths that it can take:
1) through the earth
2) through the TBM
3) through an equivalent series resistor equal to the summed resistance of the TBM and a human

The resistance of the TBM, $R_{TBM}$ (Ω), can be reasonably calculated as 2Ω [64]. However, the resistance of the earth proves to be a difficult task as the earth is highly variable, anisotropic and relatively infinite in size compared to the TBM. Therefore, there is no single, unique resistance that can be reasonably used for the earth. The worst case scenario is where the
earth has an infinite resistance, and effectively all of the current short circuits directly back into the TBM. The simple circuit is now reduced to Figure B.1(b).

![Simple circuit analysis of TBM mounted electrical system](image)

**Figure B-1: Simple circuit analysis of TBM mounted electrical system**

It is now possible to calculate a value for the magnitude of total allowable current injected into the circuit, $I_s$ (Amps), using Equation B.1:

$$I_s = i_2 \frac{R_{TBM} + R_{human}}{R_{TBM}} = (0.003A) \left( \frac{2Ω + 1000Ω}{2Ω} \right) \approx 15A$$  \hspace{1cm} (B.1)

This provides an allowable limit for $I_s$ of 15A. To comply with appropriate voltage limits (<55V), this solution also solves for the associated voltage seen by the equivalent resistance in our circuit (~2Ω) using Ohm’s Law (Equation B.2):

$$V = IR = 15A \times 2Ω = 30V$$  \hspace{1cm} (B.2)

It is shown that the voltage observed across this theoretical circuit remains at 30V, well below the allowable 55V limit.