Effectiveness of Laboratory Physical Modelling in Acquiring the Response of Induced Polarization (IP)

Yatini1*), Djoko Santoso2), Agus Laesanpura2), Budi Sulistijo3)

1)Geophysics Engineering, Universitas Pembangunan Nasional “Veteran” Yogyakarta
SWK 104 (North RingRoad) Street, Condongcatur, Yogyakarta 55283, Indonesia
2)Geophysics Engineering, Institut Teknologi Bandung, Ganesha Street No 10, Bandung 40132, Indonesia
3)Mining Engineering, Institut Teknologi Bandung, Ganesha Street No 10, Bandung 40132, Indonesia

*mail: jeng_tini@upnyk.ac.id

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Abstract. The problems of mineral exploration is how to distinguish the metallic minerals deposit based on Induced Polarization (IP) parameters. The physical modelling of IP is used to study the behavior of TDIP response. The study of simple mathematical model is carried out to obtain the theoretical curves which are presented the subsurface parameter. These curves are used as a reference to assess the result of physical modeling. The laboratory physical modelling uses tank model with size of (200x100x70) cm³, with a block as a target and water as a host medium. The results show laboratory physical modelling which has been made is quietly good. Approximate position and geometry of the target can be identified. The resistivity inversion modelling is sensitive to recognize the geometry and position, while the chargeability inversion on the distribution of metallic minerals. The quantitative correlation between chargeability and iron-ore content is obtained by Dipole-dipole and Wenner configuration.

Keywords: TDIP response, resistivity, chargeability, physical modeling, metal mineral content.

1. Introduction

Metallic minerals is well known as the metal base material and largely used in industry to meet the human needed. Attempts to obtain metallic mineral reserves continue to do. The research of electrical polarization effects in a rock that was developed by Schlumberger in 1911 became the foundation development of Induced Polarization (IP) methods. With the development of tools and theoretical understanding of the electrical properties, the method more reliable as metallic mineral prospecting tools. Currently on metal mineral exploration activities, the use of IP methods becomes a necessity. This method is better than other geophysical methods due to its accuracy in depicting the distribution of polarized regions caused by the presence of metallic mineral deposits. In the IP method, it is known the induced polarization in time domain hereinafter called Time Domain Induced Polarization (TDIP). The chargeability as TDIP response which is formulated and distinguishes subsurface polarisabilityility is indicative of metallic minerals (Siegel, 1959).

Physical modeling is widely used by other researchers to obtain a resolution of resistivity in a variety of configurations (Apparao, 1997), examines the disseminate or massive mineral (Sarma, 2009) or evaluate the depth penetration in sounding measurement (Li, et al., 2010). Physical modeling can also be used as a reliability examiner of measurements instruments and measurement methods (Majumdar, et.al., 1984). The use of physical modeling laboratory to determine behavior of TDIP responses as metal mineral content in the target done in the study. Preliminary studies showed that the response TDIP resulting from the measurement of physical models, comparable to level of iron-ore in the target (Yatini, et al., 2014). The use of water as the medium of host and block target, represents the subsurface properties of the medium. The use of Dipole-dipole and Wenner electrode configuration, gives an
overview of measurement techniques influence the response TDIP. Results TDIP response surface caused by these conditions studied, so the response behavior TDIP on physical modeling can be well understood. In this study also made mathematical modeling as a reference for assessing the effectiveness of physical modeling in obtaining TDIP response. Inversion modeling is applied to analyze the results of the physical modeling. The purpose of the physical modeling of the laboratory is to obtain quantitative relationship TDIP response to metallic mineral deposits, by analyzing the behavior of TDIP response to changing iron-ore content in the subsurface target. Mathematical formulation is made to the physical model conditions. The goal is to obtain the theoretical curves are presented subsurface parameter relationships with TDIP response. Furthermore, these curves are used as reference and evaluation of the success of physical modeling laboratory. The success of physical modeling was also evaluated by the results of the inversion Res2Dinv suitability of the condition of the model.

2. Methods

2.1 Laboratory Physical Modelling Techniques

Laboratory physical model is made in a glass container (tank model) with size of (200cm x 100cm x 70cm). Stainless steel wire with 1 mm of diameter and 10 cm of length is used as current electrodes. Non polarisable electrodes are made from pen which is contained by CuSO₄ solution. Copper wire is inserted into it as the potential porous electrode of Cu-CuSO₄. Based on the test result, this porous electrode works very well on the physical modeling (Yatini and Laesanpura, 2013). The current and potential electrodes are set on a wood which has been marked with same distance, so the point spaces will always fix to make the data acquisition is easier. Each electrodes are given a number which shows the position of measurement point. Water is used as host medium because of its chargeability value very small and close to zero (Apparao, 1997; Li, et al., 2010; Padmavathi, et al., 2014).

2.2 The Measurement of TDIP Response

The midpoint of 0 is used as reference measurement. The target is placed at the midpoint and is positioned 2 cm below the surface of the water. TDIP response measurements using IP-Meter Syscal Junior IRIS Instruments 568 series that can be used to measure chargeability and resistivity. TDIP response measurements carried out on the surface of the water.

![Illustration measurements](image)

Figure 1 Illustration measurements on physical modeling laboratory with the block target (a) (5x20), (b) (20x5) and (c) (40x5), varying in iron-ore content. Water is used as a host medium. At each target applied Dipole-dipole and Wenner configuration with spaced 5cm to get TDIP response data.

At all target applied Dipole-dipole and Wenner configuration spaced 5 cm. Block size (40cmx20cm x5cm) with iron-ore levels of 20%, 40%, 60, 70% and 80% respectively, used as a target. The measurements illustration can be seen in Figure 1. The data
obtained is apparent chargeability and resistivity that measured at the surface. While the parameter data subsurface are true resistivity and chargeability of the host and the target, the target geometry and measurement electrode arrangement, spacing and \( n \). The true resistivity and chargeability host medium obtained from the measurement of water use Soil Resistivity Box (SRB) as Table 1.

### Table 1

The TDIP response value of the target and host medium in physical modeling laboratory is used as an input in the forward modeling.

<table>
<thead>
<tr>
<th>Iron-ore content (%)</th>
<th>Fe-total content (%)</th>
<th>Targets ρ (Ohm-m)</th>
<th>m (ms)</th>
<th>Host medium ρ (Ohm-m)</th>
<th>m (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>7.07</td>
<td>16.18</td>
<td>1.48</td>
<td>36.63</td>
<td>0</td>
</tr>
<tr>
<td>40</td>
<td>14.13</td>
<td>16.40</td>
<td>1.97</td>
<td>36.63</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>21.20</td>
<td>10.40</td>
<td>1.65</td>
<td>36.63</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>24.80</td>
<td>11.20</td>
<td>2.62</td>
<td>36.63</td>
<td>0</td>
</tr>
<tr>
<td>80</td>
<td>28.30</td>
<td>8.61</td>
<td>4.23</td>
<td>36.63</td>
<td>0</td>
</tr>
</tbody>
</table>

\( ρ \) = resistivity \( \rho_a \) = apparent chargeability

### 2.3 Mathematical Formulation of the Target

Formulated TDIP response of the model sphere or block with host homogeneous isotropic medium. Response due to the target in a homogeneous isotropic medium, obtained by solving the Laplace equation \( \nabla^2 V = 0 \) with the boundary condition suitable conditions. Settlement for sphere model with radius \( R \) is the IP response for of two potential configuration at the surface.

\[
\begin{align*}
\frac{\rho_a}{\rho_1} &= \left[ 1 + \left( \frac{\rho_1 - \rho_2}{\rho_1 + 2 \rho_2} \right) \right] R^3 \left( \frac{(2x^2 - d^2)}{(x^2 + d^2)^{5/2}} \right) \quad (1) \\
\frac{m_a}{m_2} &= -3 \left( \frac{\rho_1^2}{(\rho_1 + 2 \rho_2)^2} \right) R^3 \left( \frac{(2x^2 - d^2)}{(x^2 + d^2)^{5/2}} \right) \quad (2)
\end{align*}
\]

Where \( x \) is the distance of the center of the sphere against the receiving surface, \( d \) is the depth of the sphere, \( \rho_1 \), \( \rho_2 \) and \( m_1 \), \( m_2 \) are resistivity and chargeability on medium and spheres respectively. While \( m_a \), \( \rho_a \) are apparent chargeability and resistivity measured surface respectively. The solution of the Laplace equation of block model with Dipole-dipole configuration is done.

The TDIP response ie. resistivity and chargeability (equations 1 and 2) is expressed as a curve which is a description of changes in TDIP response laterally. In this study, the software Res2DMod (Loke, 2002) have been selected as the forward modeling process. The forward modeling yield curve describes the relationship TDIP response to the subsurface parameters and measurement techniques. The theoretical response curves to be modeled subsurface with the sub-surface parameter values and a particular electrode configuration. The data in Table 1 was used as a forward modeling. The theoretical TDIP response was obtained for all values of \( n \).

In this study, theoretical curve stimulation results of various spacing at the same depth. In addition, at different depths in the same spacing. Comparison of these curves can be used to select the appropriate spacing on the desired target depth. Selection of spacing used and the target depth in the laboratory physical modeling is based on the result of stimulation in theoretical curves. Physical modeling laboratory created in this study, the block target is at a depth of 2 cm. TDIP response curves theoretically generate maximum value at 5 cm spacing. Therefore, it is most appropriate when used 5 cm in spacing (Yatini, et al., 2015). The result of theoretical curve stimulation, it can be applied in the true field. The selection of the most suitable spacing to find the target with the desired depth. This will greatly help design survey field.

### 3. Results and Discussion
In this study measured target at a depth of 2 cm with a configuration Dipole-dipole and Wenner. Target block (20x5), (40x5) and the block (5x20). Blocks (5x20) is a block with a width of 5 cm and 20 cm high. Blocks (20x5) if the block width of 20 cm and height 5 cm, the block (40x5) if the block width of 40 cm and a height of 5 cm.

3.1 Matching the curve
Good results were obtained from measurements of resistivity and chargeability on physical modeling created. The first reference to theoretical shape of the curve is symmetrical, the symmetry measurement results were seen in all \( n \). The results of all the curves on the target are coherent. The maximum amplitude of the curve lies at the midpoint, ie the top of the target. Between theoretical and measurement results show good agreement for all levels of iron-ore. Figure (2) is the theoretical and measuring curves at block target (5x20) 20% iron-ore content with Wenner configuration. A good correlation is shown by the results of measuring and theoretical. All of the measurement curves show positive correlation to iron-ore content in the target both for dipole-dipole or Wenner configuration. The greater of iron-ore content of measured block target, the average amplitude of chargeability measurement result is also greater.

The measurement of resistivity parameter in block target also show a good result (Figure 2b). All the curves are coherent and symmetrical at zero point. The high response is observed in zero point at all \( n \) with amplitude fluctuation in range of (30-50) Ohm-m. There’s no significant amplitude variation of resistivity response to the changing of iron-ore content. At all iron-ore contents, the resistivity response shows relatively constant value. The fluctuative amplitudes appear at value of 37 Ohm-m in the left-right side consistently in all iron-ore contents which show resistivity value as host medium resistivity.

The amplitude of theoretical resistivity curve decreases due to value of target resistivity which is smaller than host medium resistivity. The theoretical results show the amplitude drops due to the value of host medium resistivity. The measurement resistivity curves show amplitude which increases. It is caused by the polarization phenomenon on the block target surface. The polarization effect on the highly conductive target which is sunk in the water as conductive host medium cause the resistivity value of the target increases. It commonly happens in physical modelling using host fluid or very conductive medium (Apparao, 1997; Sarma, 2009).

The curve matching with the measurement result in this research is done to assess accuracy of physical modelling in describing the subsurface condition. Suitability of theoretical response and measurement are shown by the difference between both of

Figure 2 (a) The chargeability and (b) resistivity measurement curve and theoretical curve of the block target (5x20) with 20% iron-ore content, Wenner configuration, for \( n=1 \) to 3. \( n=1, T \) : theoretical curve for \( n=1 \) and \( n=1, U \) : measurement for \( n=1 \).
The average difference of block target are 15.3% and 19.7% for Dipole-dipole configuration and 14.7% and 19.3% for Wenner configuration. The average difference between theoretical and measurement value in laboratory physical modelling in this research is less than 20%. It shows if the physical modelling which has been made in this research is quietly good. The difference of resistivity value is less than chargeability value. In general, incompatibility on chargeability value is looked bigger than in resistivity value both on Dipole-dipole and Wenner configuration. It is caused by the accuracy of Syscal as measurement tool which is used.

3.2 Inversion Modelling
One of processing steps on IP measurement data is inversion to obtain true resistivity and chargeability value. The inversion of TDIP measured data in physical modelling is done by Res2DInv software (13). The use of Res2DInv for inversion in this research is based on some considerations. The software resolution on block model distribution are used to generate the inversion initial model which affects the geometry interpretation. In the Res2DInv software which is used, the smallest block model is able to be made as rectangular model with ¼ of side length from the smallest electrode space. If this rules are applied in laboratory physical modelling which 5 cm of space, then the smallest block model which can be generated by software is a rectangular with size (1.25 x 1.25) cm². The width of block model is 5 cm. Because of the block target size is bigger than 1.25 cm, the target dimension will be well detected. Unfortunately, this software has a weakness there is if the input data has large range, the inversion will unstabil and the damping factor should be upgraded and it can cause quietly big RMS error (Loke, 2003).

The resistivity value of the block is 16 Ohm-m and water is 36.63 Ohm-m. The inversion result for block model (40x5) is shown in Figure 3. The result at block target (5x20), (20x5) almost same. High anomalies appear precisely in the block position. The geometry boundaries are suitable with anomaly boundaries. Host medium around it has value 30-35 Ohm-m, it is suitable with true resistivity value of water. The position and geometry of the target block can be obtained from the resistivity inversion. From these results, it can be stated if the physical modelling which has been made is quietly good because it can bring out subsurface parameter very well. Although the resistivity contrast of the block target and host medium is not too big, the position and geometry are described very well on the resistivity inversion modelling. The block target boundaries to host medium are described is suitable with the anomaly boundaries. The chargeability inversion modelling shows similar result. High chargeability value indicates high content of iron-ore. High chargeability value is concentrated in the center part of the target. Resistivity inversion modelling is sensitive in describing geometry, while chargeability is more sensitive in describing distribution. The result of inversion modelling from measured TDIP data also can be used to assess the effectiveness of laboratory physical modelling in describing the TDIP response behavior.
The result of inversion modelling with block target (20x5) for iron-ore content (a) 20%, (b) 40%, (c) 60%, (d) 70%, and (e) 80%, dipole-dipole configuration; n=1-8. Rectangular line is block target position in subsurface.

The measurement of TDIP response is carried out on block target with various content. The inversion modelling result of Dipole-dipole configuration with block target (20x5) using iron-ore content 20%, 40%, 60%, 70%, and 80% are shown in Figures 4 and 5 respectively.

At all iron-ore contents, the resistivity anomalies appear very clear and consistent. The boundaries of resistivity anomaly show precisely the depth and block target geometry (Figure 4). In the inversion modelling of resistivity, block target resistivity and position are decribed very well. Resistivity changes due to the changing of iron-ore content at block target. Its value ranges from 60 to 120 Ohmm, meanwhile surrounding it is the host medium with various resistivity values from 15 – 40 Ohm-m. The result of resistivity inversion modelling for block target (40x5) almost shows the same result.

Figure 5 is the result of chargeability inversion on target block (20x5) with iron-ore content from 20% to 80% using Dipole-dipole configuration. Chargeability anomaly is seen exactly in the block target position for all iron-ore content consistently. The width of the target is seen at all content and shown at values boundary (2-6) ms. The high chargeability is located at the center of target body for all iron-ore content. At Wenner configuration, position and width of the block target appears at inversion modeling results. Chargeability parameter really shows the increased value due to the increases of mineral content in the target. The strongest chargeability anomaly is 80% of iron-ore content. The same result is found in the block target (5x20) and (40x5). The result of resistivity inversion modelling always describes the target geometry and position. Chargeability inversion modelling can show the width and depth of the target, but it is not sensitive for geometry. The present of consistency of chargeability anomaly changes due to the changes of iron-ore shows if both of them are connected directly.
Figure 5 The chargeability inversion result with dipole-dipole configuration, block target (20x5) for iron-ore content (a) 20%, (b) 40%, (c) 60%, (d) 70%, (e) 80%. The rectangular line is the block target position in subsurface.

3.3 The Slicing of Inversion Modelling

The slicing at various depth from inversion modelling of measurement data is done to obtain quantitative correlation of TDIP response to iron-ore content. The depth slicing is made by inversion modelling result as shown at Table 2. The slicing names for inversion modelling result are \(d_1\)-\(d_8\) for Dipole-dipole configuration and \(w_1\)-\(w_8\) for Wenner configuration.

This step is applied for all inversion results by using measurement data. The result of inversion modelling is block target with Dipole- dipole configuration and Wenner configuration for all iron-ore contents. The TDIP response curves to iron-ore content are obtained from all slices. For example, slice of \(d_8\) is chosen for Dipole- dipole configuration because of the slice is crossing trough the center of the block (Figure 6).

From the curves in Figure 6a, it can be seen if the greater of iron-ore content in the block target, the value of TDIP response is greater as well and it is shown by its amplitude. It occurs both on the dipole-dipole configuration and Wenner configuration. The width of the curve indicates the width of the block target for Dipole-dipole configuration. The curve at iron-ore content ranges from 20% to 80% are coherent each other with maximum value at zero point. It shows that the strongest value of TDIP response at the middle peak of the target and it is smaller on the side of the target with all iron-ore content. The results are suitable with the hypothesis, the greater of metallic mineral content then the TDIP response is greater as well.

### Table 2 Depth incision inversion results.

<table>
<thead>
<tr>
<th>Dipole-dipole configuration</th>
<th>Incision</th>
<th>Depth (cm)</th>
<th>Wenner configuration</th>
<th>Incision</th>
<th>Depth (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d1</td>
<td>-0.214</td>
<td>w1</td>
<td>-0.313</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d2</td>
<td>-0.427</td>
<td>w2</td>
<td>-0.625</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d3</td>
<td>-1.282</td>
<td>w3</td>
<td>-1.875</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d4</td>
<td>-2.179</td>
<td>w4</td>
<td>-3.188</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d5</td>
<td>-3.166</td>
<td>w5</td>
<td>-4.631</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d6</td>
<td>-4.252</td>
<td>w6</td>
<td>-6.219</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d7</td>
<td>-5.446</td>
<td>w7</td>
<td>-7.966</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d8</td>
<td>-6.759</td>
<td>w8</td>
<td>-9.888</td>
<td></td>
</tr>
</tbody>
</table>
Slice of inversion resistivity curve in Figure 6b shows no specific pattern of the amplitude to iron-ore content. At ore contents of 20% and 40% the amplitude is increases, at 60% it decreases but it increases again at iron-ore content of 70%. After that, it decreases again in the iron-ore content of 80%. The width of the curve shows the width of the target for Dipole-dipole configuration. For the block target (5x20) and (40x5) are also generated the slicing of chargeability and resistivity curves as shown in Figure 6.

The quantitative correlation between TDIP responses to the iron-ore content is obtained from the slicing of inversion result in Figure 7a and 7b as the result of chargeability and resistivity parameter. The curve in Figure 7a shows coherent and congruent curve for all depths which are obtained from Dipole-dipole configuration and Wenner configuration. The same values are showed on 20% of iron-ore content. It shows if the smaller of iron-ore content the chargeability value will be smaller as well and evenly spread in the each parts of target.

The graph of chargeability increases gradually from small iron-ore contents, starting from 70% and rapidly increases with slope more than 80%. The characteristics of that curve by Apparao and Sarma are expressed as the boundary of disseminated and massive minerals. The boundaries are obtained in this research is 70% of iron-ore content. If the iron-ore content in the target is less than 70%, that target is disseminated minerals. But if the target is greater than 70%, the target is massive minerals. If it is expressed in Fe-total, it will be obtained the boundary between disseminated and massive minerals in 25% of iron-ore contents.
The similar curve as in Figure 7 is obtained for block target (5x20) and (40x5), however the chargeability correlates exponentially to the of iron-ore contents (Table 3). All the curves are identical and show exponential correlation with different exponential index. From all of the curves are obtained the boundaries between massive and disseminated minerals there are 70% of iron ore and 25% of Fe-total. The result of resistivity parameters are different as shown in Figure 7b, the resistivity value in all contents show almost same values. It shows if the variable that affecting resistivity is not only dominated by metallic mineral contents. Porosity, clay content, temperature, and some factors influence the resistivity value.

On this research is used resistivity value for target and host medium as shown in Table 1.

The resistivity contrast range from 2.2 to 4.2 Ohmm. The ideal resistivity contrast in the physical modelling is 100 (Apparao, 1997). Although the resistivity contrast is small, the results of inversion modeling for block target is quitely good. The linkage between resistivity and iron-ore content in the target can’t be obtained from laboratory physical modelling.

The resistivity method is sensitive to determine the geometry, while the IP method is more sensitive to know the metallic mineral content in the subsurface. Because of that in IP survey with metallic mineral target is difficult to be interpreted based on resistivity value only. To know the presence of metallic mineral in the survey area it should be observed from the value and distribution of chargeability.

### Table 3  The quantitative relationship chargeability to iron-ore and Fe-total content at block targets.

<table>
<thead>
<tr>
<th>Targets</th>
<th>Dipole-dipole Configuration</th>
<th>Wenner Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Iron-ore (x)</td>
<td>Fe-total (x’))</td>
</tr>
<tr>
<td>Block (5x20)</td>
<td>m=0,11</td>
<td>exp(0,034)x</td>
</tr>
<tr>
<td>Block (20x5)</td>
<td>m=0,04</td>
<td>exp(0,09)x</td>
</tr>
<tr>
<td>Block (40x5)</td>
<td>m=0,92</td>
<td>exp(0,032)x</td>
</tr>
</tbody>
</table>

m: chargeability (ms), x and x’: iron-ore and Fe-total content(% volume).

### 4. Conclusion

The theoretical curves which have been derived form mathematical formulation of subsurface model are suitable to be used as examiner for the success of laboratory physical modelling. The test result shows if the laboratory physical modelling which has been made is quietly good. The result of inversion modelling on block model also shows the similar result. Because of that, the physical modelling which has been made is effective to understand the behavior of TDIP response. Subsurface parameter includes are position and geometry which can be identified by the result of inversion modelling from laboratory physical modelling data. The resistivity inversion modelling is more sensitive to identify geometry and position of the target, while the chargeability inversion is more sensitive to identify the distribution of metallic mineral in the target. From the result of laboratory physical modelling, the boundary of disseminated and massive mineral can be obtained with amount of 70% in iron-ore.

This research obtains quantitative correlation between chargeability and iron-ore content in several targets with Dipole- dipole and Wenner configurations. Both of them are connected exponentially with different exponential index for different target. Meanwhile the correlation between resistivity and metallic mineral content in the target hasn’t been obtained quantitatively from physical modelling. The handling
procedure of physical modelling has been resulted for time domain IP method especially to determine the correlation between TDIP responses to the iron-ore content. This procedure is expected to become standard procedure for handling the physical modelling of IP method in time domain.

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