# Self-Potential and 2-D Resistivity Application for Groundwater Exploration in Fracture Reservoir

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Self-Potential and 2-D Resistivity Application for Groundwater Exploration in Fracture Reservoir

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Abstract

The high demand for various consumption of water related to the domestic and industrial usage is increasing rapidly. Alternative water supply with less pollution and economic values is needed to support the demand. The self-potential and 2-D resistivity methods were used to identify the flow pathways of the water and potential groundwater zones in Johor, Malaysia by measurement of potential difference between two non-polarizable copper electrodes and resistivity distribution of the subsurface respectively. The recharge zone of the aquifer was identified with negatively of potential values (0 to -140 mV) while positively values (0 to 140 mV) show the discharges zones for this area. The self-potential result shows the flow pathways of groundwater at the direction of the southeast to northwest of the study area. A potential groundwater zones identified at resistivity values of <100 Ωm with depth >50 m. The highly contrast of resistivity values indicate as the fracture/fault for this area.

Keywords: Self-potential, 2-D resistivity, surface water, groundwater

1. Introduction

Geophysical methods are rapid, non-destructive, relatively inexpensive, and can vastly improve the characterization of the shallow subsurface. Self-potential (SP) is one of the non-invasive geophysical methods that measures the natural potential of the Earth (Nyquist & Osiensky, 2002). The method is an established geophysical method that has been applied for various application and research, such as mineral explorations, oil well
logging, geothermal explorations, hydrogeological surveys, and many other applications within the scope of the environmental studies and engineering. The electrical method has been widely used in monitoring the groundwater occurrence within a fractured rock. Fractures in rock are important pathways for groundwater flow and contaminants migration. The rate and direction of groundwater flow at a given location is driven by hydraulic gradient which also determined by the strength of recharge and discharge. The topography and fractured influence the groundwater flow path directions. The flow pathways follow the direction of the strike and topography toward local stream. The groundwater flow classified into three components; down the hydraulic gradient, downdip, and along the strike (Fan, Toran, & Schlische, 2007). The adjacent boreholes were monitored with the application of one of the primary techniques such as pumping tests (Domenico & Schwartz, 1997) because it gives excellent measurement of fluid flow and transport properties as hydraulic transmissivity of aquifers. However, due to heterogeneity of fractured rock system with a greater volume it may be impossible to extrapolate with a single measurement. The self-potential approach generally measures the electric potential which occurs naturally in the ground surface and the technique can be used in the identification of groundwater flow path in a large scale. Self-potential occurs below the soil surface which caused by electrokinetic or streaming potential produce by fluid and heat fluxes in the ground, diffusion potentials across boundaries between regions of different chemical composition and redox reactions around orebodies and buried metallic objects (Fritjof & Graham, 2003). Generally, the streaming of water through porous material and fractures in the subsurface produces an electrical potential gradient, known as streaming potential along the flow path (Birch, 1993, 1998; Doussan, Jouniaux, & Thony, 2002; Maineult, Bernabe, & Ackerer, 2005).
The potential difference fluctuates due to variation in electric current of the ground. A negative self-potential anomaly is associated with a recharged area or downward flow of the water movement while positive anomalies indicated by the positive anomalies with the strong lateral flow of water movement (Bogoslovsky & Ogilvy 1973; Ogilvy, Ostrovskij, & Ruderman, 1989; Leonard, Cyril, & Anthony, 2010).

In addition, the pioneer of resistivity sounding, and profiling technique gives the 1-D model of the subsurface which is not appropriate in mapping the geological structures of higher complexity. The 2-D resistivity model provides more realistic information and visualization of the subsurface, where the resistivity varies in vertical and horizontal direction along the survey lines. The values are mapped even in the presence of complex geological condition and topography (Loke, 1997a). Recently, the 2-D resistivity method was successfully used in subsurface exploration in various environment including bedrock detection, geological mapping and groundwater exploration (Zhou, Matsui, & Shimada, 2004; Hsu, Yanites, Chin chen, & Chen, 2010; Rao, Prasad, & Reddy, 2013). The high demand in various consumption of water related to the domestic and industrial sector such as agricultural, factory and public supply has increased rapidly. Thus, alternative water supply, such as groundwater is needed to support the current usage beside provide more economic and less pollution compared to other water resources. However, a designation of foundation tube well with a suitable location for extracting maximumly the water resources should be chosen wisely based on consideration of geological condition and other parameters. A wrong judgment in selecting a suitable location may affect unproductive production in term of cost, time, and productivity. Groundwater assessment using geophysical approach is required to encounter these challenges in determining the potential groundwater zones besides
provided more comprehensive result. In this research, the self-potential method was applied with the correlation of 2-D resistivity for imaging the flow of groundwater in part of Johor area (Figure 1).

2. Background Theory

Electrokinetic’s potential is produced when the electrolyte passes through a porous or capillary slit and the potential is measured along the capillary. The potential which is generated from this phenomenon is categorized as a streaming potential which can be expressed as follows:

\[ E_K = \frac{\varepsilon \rho C_E \delta P}{4\pi \eta} \]  

(1)

whereas;

- \( E_K \) = Electrokinetic’s potential
- \( \varepsilon \) = dielectric permittivity of pore fluid
- \( \rho \) = electrical resistivity of pore fluid
- \( \eta \) = dynamic viscosity of pore fluid
- \( \delta P \) = the change of pressure
- \( C_E \) = coupling coefficient of electrofiltration

\( C_E \) represents the physical and electrical parameter of electrolyte passes through the medium. The movement of the fluid generates a potential gradient along the flow path due to the interaction between pore fluid movement and an electrical double layer which is known as the streaming potential.

2D resistivity method utilizes direct current to investigate electrical properties of subsurface by measuring resistivity distribution of the materials. Fluvial, lacustrine sediments, bedrock, structural features such as faults exhibit a large contrast in
resistivity values (Asry, Samsudin, Yaacob, & Yaakub, 2012). The electrical resistivity of the materials depends on the combination of ohmic and dielectric effects which are related to lithology of subsurface (Edwin & Cahit, 1988). The fundamental theory of 2-D resistivity is related to the Ohm’s Law which can be expressed as;

\[ \rho_a = k \frac{V}{I} \]  

whereas;

- \( \rho_a \) = Apparent resistivity
- \( k \) = Geometric factor of the electrode array
- \( V \) = Voltage
- \( I \) = Current

The \( k \)-values plays an important role in determining the depth of investigation for 2-D resistivity surveys. The electrical resistivity of sediments and rocks is a function of porosity, saturation, the resistivity of pore fluids and solid phase, and material structure. It has been observed for many cases that water-bearing rocks varies as the inverse square of the porosity. The Archie’s law (Archie, 1942) describes how resistivity depends on porosity of ionic conduction in the pore fluid.

3. Methodology

3.1 Study area and geological setting

The study area (Figure 1c) is located at Johor where it is generally covered by Tertiary sediment similar to Batu Arang and others Tertiary basins of West Malaysia, and similar to Late Tertiary age (Staufer, 1973a). In addition, Burton in 1964 mentioned
the possibility of a Quaternary age for these sediments, with consideration of unconformity overlying alluvium in Early Pleistocene or Pliocene age. Figure 1b shows the rock unit of the study area is granite, adamellite, and minor granodiorite from Belumut granite (Kia et al., 2012). The units showed various dip directions of the sediments, changes the lateral thickness and depth rapidly to older rocks (i.e. granite and volcanic rocks). The shallow depth sediments area is composed of sand clay, clay, sand, and shale while the deeper geology is made up of granite, volcanic rock, tuff, and quartzite. From previous facies analysis on the outcrop done by previous geologist showed the lithology outcrop are mostly light-coloured which may indicate the lack of decomposed organism (carbon) within them and the layers are also not fully consolidated sandstone ranging from medium grained to coarse grained with a wide range of grain sizes. The dominant mineral present are quartz followed by feldspar (Meng, Jamin, Mohamed, & Mun, 2016). The sediment was deposited in a fluvial environment which includes floodplain and abandoned channel predominantly made up of mudstone, siltstone, and sandstone. Most of the mudstone and siltstone that are rich in organic materials are light grey to dark grey in colour (Said, Rahmah, Hamid, & Ariffin, 2003). The area is mostly low-land and it is surrounded by hills with different elevations.

3.2 Field procedure

3.2.1 Self-potential

In the self-potential method, two non-polarizable copper electrodes and two porous pots with ABEM SAS300 was used for data acquisition. The copper electrodes were suspended in a supersaturated solution of copper sulphite, CuSO$_4$ inside a porous
container. One of the electrodes is used as a fixed reference called base station and is located outside the survey lines. The location of the base is carefully selected with uniform streaming potential to reduce telluric and cultural noises for better data accuracy. The CuSO$_4$ are sensitive to temperature changes, 1.2 mV/°C (Jardani, Dupont, & Revil, 2006), thus it is important to reach thermal equilibrium between the porous pot and the surrounding soil before starting the measurements. The $P_1$ pole (negative terminal) at ABEM SAS300 was connected to the base electrode while $P_2$ pole (positive terminal) was attached to a rover electrode. The base station reading was repeated for every two hours after the measurement of the rover station for a drift correction. To obtain the highest consistency reading, the holes of each station were dug deeply enough to penetrate the surface soil with intervals for of each station ranging from 3-5 m. Self-potential was measured as the difference in electric potential between the reference electrode (base station) and another electrode (rovers). The measurement of the data was done for three times where four different values were given for each measurement. There was a 3 minutes time interval before each repetition of data measurements after placing the electrodes (rovers) on the ground. The data was taken in three repetitions to improve the signal-to-noise ratio. In data processing, Surfer8 software was used in mapping and contouring the data to produce a residual self-potential map.

3.2.2 2-D Resistivity

In 2-D resistivity survey, ABEM SAS4000 with Pole-dipole array and 5 m minimum electrode spacing system were used to acquire the data. The Pole-dipole array was chosen since the array can give a deeper penetration depth with good data resolution.
Three survey lines were designed in such way to fulfill the objective of the study. The lines are L1, L2, and L3 with a distance of 800 m, 600 m, and 800 m respectively. The survey used 41 electrodes during each measurement and they were connected to a multichannel cable and ES10-64C electrode selector for the data measurement. Roll-along technique was applied in certain cases by extending the data measurement with overlapping of 50 m for each next spread of acquisition. The resistivity data was processed in Res2dinv software for inversion model and Surfer8 software for interpretation and correlation. The results obtained were presented in 2-D resistivity inversion model where the range of resistivity values were indicated by a color scale.

4. Results and Discussions

4.1 Self-potential

The self-potential (SP) data presented in Figure 2a and 2b was obtained by using the contouring and interpolation of the data by Kriging algorithm to optimize and smoothness the data from the Surfer8 software. Self-potential anomalies are associated with the presence of water in subsurface structures and the flow of water pathways through the ground (Jinadasa & Silva, 2009). In this survey, the electrochemical sources were neglected in the interpretation because it was considered that the study area has no indication of significant oxidation and reduction reactions associated with biodegradation of the solid waste materials such as leachate or contaminants flow of water. The thermoelectric effect which is related to temperature variation was also neglected since it showed minor contribution to the data are neglected, and the observed SP field is considered primarily to be created by electrokinetic sources which is related fluid flow in the subsurface. The magnitude of the potential field is inversely
proportional to the electrolytic concentration of pore fluid, hence the maximum contribution of the SP anomaly is generated by the flow of freshwater (Bogoslovsky & Oglivy, 1973). In this study, the potential values cover from -140 mV to 140 mV (Figure 2a). The interpretation of the SP data is based on the waterflow path according to its values. The contour reveals a spatially non-uniform distribution over the study area where a distinguishable positive anomaly with a high anomaly can be located at the edge of the map. The first anomaly is a large positive SP zone near the reference electrode that increase positively towards the northwest of the map. This positive anomaly was suspected as groundwater discharge at the base of a steep slope (Corwin & Hoower, 1979). The second anomaly is the SP zone with the highest negative values and it is located at the edge of the northwest direction which represents the recharge area. In the map, low potential values from -140 mV to positive values were distributed at the southwest of the map. The streaming potential of groundwater is usually indicated by the negative anomaly of the profile (Colangelo, Lapenna, Perrone, Piscitelli & Telesca, 2006). The negative SP anomalies are normally associated with the downslope movement of the subsurface water (Corwin, 1990; Panthulu, 2001). The location considers having a slight topographic depression (Figure 2b) which could indicate the lateral variation in material properties or vertically descending flow of bedrock fault or fracture zone. SP distribution associated with steep topography has been examined and reported by the previous researchers which showed signs relative to shallow groundwater flow (Corwin & Hoover, 1979; Ernston & Scherer, 1986). This shows that the accumulation of the surface water which had flowed to this region. The magnitude of the direction shows the movement of the water; high magnitude indicates the rapid
flow of the water for the area. Other than that, the water discharging and charging activities for this area consider actively occur due the wide range of potential values.

### 4.2 2-D resistivity

The 2-D resistivity data presented in 2-D inversion model of resistivity. The position of the first electrode location was corrected and the filtered data were inverted using the Least Square Inverse technique with smoothness constraint and Gauss-Newton optimization technique using Res2Dinv (Loke, 1997a; Loke, 1997b). The calculated apparent resistivity values of the model block were compared with measured apparent resistivity values. It is adjusted iteratively until the values of the model achieved high closeness with the measured apparent resistivity values. A root mean square (RMS) value of less than 35% was observed which indicated a high similar model block to the apparent resistivity.

Figure 3a shows the 2-D resistivity inversion model of L1 with resistivity values ranging from 1-10000 Ωm with the depth of investigation of 150 m. From this model, the saturated zone was identified with resistivity values of <100 Ωm at depth of >50 m. This zone was classified as the potential groundwater zone. The low resistivity values, at the top layer of the profile along distance of 0-350 m indicate the accumulation of the surface water and this is closely agreeable with the SP result. The contrast zone was interpreted as fracture/fault (black dashed lines) which may act as potential pathway for the groundwater to seep upward due to the difference in pressure gradient. High resistivity values of >700 Ωm indicates as the cap layer for the aquifer. 2-D resistivity model in Figure 3b shows the continuation of the profile L1. The subsurface features were identified as the fracture/fault zone at depth of >50 m due to the contrast in the
resistivity values. Several isolated zones of low resistivity values (1-100 Ωm) were associated with the saturated weathered layer. A resistivity region of >700 Ωm was classified as the cap layer for the aquifer with the depth of >50 m. A low resistivity region with the depth of <50 m was associated with the water movement from the surface which had accumulated in the region. Figure 3c shows the 2-D resistivity inversion model of L3 with the depth investigation of 150 m. The result of this profile showed good correlation between lines L1 and L2 as low regions of resistivity at depth of <50 m indicated the percolation of surface water at distance of 0-300 m. The region with resistivity values of <100 Ωm indicates the indicated saturated zone for the aquifer with the depth of >50 m.

In addition, the saturated zones for all three profiles, L1-L3 showed the resistivity values of <100 Ωm, which may indicate the presence of clay and sand, with the correlation of geological setting of the area. According to Telford (1990), the resistivity values for clay varies from at 1-100 Ωm, which agrees with Abidin, Saad, Ahmad, Wijeyesekera and Baharuddin (2014). The authors stated that the resistivity values for waters at the surface and natural condition vary from 1-100 Ωm. The presence of clay and other finer sediments enhance the subsurface material in retaining the water from migrating due to porosity and permeability factors. This results in low resistivity values of the materials compared to coarser soil such as sand or gravel which tends to produce high resistivity values. Finer sediments with fine grains size, such as clay soil consist high mineral composition of kaolinite and illite which causes the current to flow easier with less resistance, resulting in low resistivity values (Abidin et al., 2017). The variation in resistivity values is due to several factors such as the concentration and types of iron innate within the pore fluid and the grain matrix which
influences the rate at which current is carried by the mineral irons (Griffith & King, 1981). Other than that, in sand/gravel formations the resistivities values are ranging between 40-400 Ωm to represents the potential groundwater zones (Ismail, Schwarz, and Pederson, 2011). The resistivity values are inversely proportional to water content and dissolved ion concentration (Liu & Evett, 2008). The saturated zone is caused by the fractures in the hard rock which allows the water to seep through and trapped inside it. The resistivity values that are low were associated with great degree of fracturing (Loke, 1997a), which indicates that the saturated zone for this locality classified as a confined aquifer. Resistivity values ranging from 700-3000 Ωm in this locality were interpreted as the presence of sandstone. Fractures plays an important role in controlling the secondary porosity of the reservoir (Warren & Root, 1963). Generally, the secondary porosity resulted due to mechanical processes such compaction, deformation and fracturing (Schön, 2015).

5. Conclusion

The flow of the water was successfully defined with the correlation of self-potential and 2-D resistivity methods. The result of 2-D resistivity was used to confirm the ambiguity that arises in self-potential interpretation. From the self-potential result, the flow pathways of groundwater are determined at the direction of the southeast to northwest of the study area. Negative potential values (0 to -140 mV) were identified as the accumulation zone of the surface water as it moves due to the potential gradient, while positive potential values (0 to 140 mV) represent the discharge zone of the study area. In 2-D resistivity result, the subsurface characteristics of the profile lines show the surface water identified at the depth of <50 m meanwhile at the depth of >50 m, the
saturated zone with resistivity values of <100 \ \Omega \ m \ was \ classified \ as \ the \ potential \ groundwater \ zones. \ A \ low \ resistivity \ region \ associated \ with \ water \ movement \ from \ the 
surface \ and \ accumulate \ in \ the \ region. \ The \ highly \ contrast \ in \ resistivity \ values \ shows \ the 
presence \ of \ fracture/fault \ line \ with \ several \ isolated \ zones \ of \ low \ resistivity \ values \ (1-100 \ \Omega m) \ associated \ with \ the \ saturated \ weathered \ layer. \ The \ correlation \ of \ both \ results 
shows \ the \ accumulation \ of \ the \ surface \ water \ which \ flows \ to \ this \ region \ as \ water 
discharging \ and \ recharging \ activity \ for \ this \ area \ consider \ actively \ occur \ due \ to \ the \ wide 
range \ of \ potential \ values. \ Table \ 1 \ shows \ the \ summary \ of \ the \ result.

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Figure 1: a) Map of Malaysia; b) Geological map of the study area; c) Map of study area (planar view)

Figure 2: Self-potential contour map (planar view); b) Self-potential contour map with topography
Figure 3: 2-D resistivity inversion model; a) L1, b) L2 and c) L3
Table 1: Summary of the result

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<th>Values/ Anomaly</th>
<th>Descriptions</th>
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<td>Positive anomaly (0 to 140 mV)</td>
<td>Associated to groundwater discharge</td>
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<tr>
<td></td>
<td>Negative anomaly (0 to -140 mV)</td>
<td>Associated to groundwater recharge</td>
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<tr>
<td>2-D Resistivity</td>
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<td>Saturated zone (Potential groundwater)</td>
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<td>&gt;700 Ωm</td>
<td>Cap layer for the aquifer</td>
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<td></td>
<td>Contrast zone</td>
<td>Presence of fracture/fault</td>
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