Application of Electrical Resistivity Method (ERM) in Groundwater Exploration

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Abstract. The geophysical method which dominant by geophysicists become one of most popular method applied by engineers in civil engineering fields. Electrical Resistivity Method (ERM) is one of geophysical tool that offer very attractive technique for subsurface profile characterization in larger area. Applicable alternative technique in groundwater exploration such as ERM which complement with existing conventional method may produce comprehensive and convincing output thus effective in terms of cost, time, data coverage and sustainable. ERM has been applied by various application in groundwater exploration. Over the years, conventional method such as excavation and test boring are the tools used to obtain information of earth layer especially during site investigation. There are several problems regarding the application of conventional technique as it only provides information at actual drilling point only. This review paper was carried out to expose the application of ERM in groundwater exploration. Results from ERM could be additional information to respective expert for their problem solving such as the information on groundwater pollution, leachate, underground and source of water supply.

1. Introduction
Rapid interest in recent years in underground sources had led for more intensive studies of the geometry and properties of aquifers. Groundwater is a very important component of water resources in nature. Groundwater is defined as subsurface water that fill in soil pore spaces and in fracture of rock formations [1]. It is known as an alternative water supply for all living things. The problem faces by engineers is to determine the exact location of groundwater zone in subsurface layer. Geophysical is the application of physics that study the earth by taking measurement at or near the surface of earth [2]. Geophysics has played a useful part in such investigations for many years in improving the instruments and development for better result in widening its applications. Electrical Resistivity Method (ERM) is part of geophysical methods which used as preliminary step involve in any groundwater exploration. ERM has been applied for many years to determine the thickness of layered media as well to map geological environment of existing aquifer. It has been effectively used for groundwater due to simplicity of the technique, efficient and non-destructive of implementation in producing the subsurface imaging compare to conventional method [3]. Table 1 indicate the comparison between the conventional method and ERM in groundwater exploration. Furthermore, with support borehole data and profile image produced from this method reliable information regarding groundwater and location of underground layers could be obtained.
Hence, this paper briefly discusses the application of ERM based on groundwater exploration. It also to assist and convince engineers to apply this technique compare to conventional method.

Table 1. Comparison between conventional method and ERM in groundwater exploration.

| Conventional method                                      | ERM                                                                 |
|--------------------------------------------------------|----------------------------------------------------------------------|
| Provide information at drilling point only.             | Offer larger data coverage.                                         |
| Lacks equipment and application for difficult accessibility condition. | Capable to conduct in difficult accessibility situation.             |
| Destructive method (changes the nature of the ground).  | Suitable for investigation of saltwater intrusion,                  |
|                                                        | groundwater pollution, indicate shallow aquifer for water resources, |
|                                                        | contamination, leachate etc.                                        |
| Expensive and limited.                                  | Non-destructive method (observe the ground without permanently changing or altering its characteristics). |
|                                                        | Generally effective in terms of cost and time consuming             |

2. Resistivity Theory

ERM basically conducted to measure and map the resistivity of subsurface materials [4]. It also refers as survey that carried out to present the image of electrical properties of the subsurface by passing an electrical current along many different paths and measuring the associated voltage [5]. ERM is based on the response between the earth and the flow of electrical current. It sensitive to variations in the electrical resistivity of the subsurface measured in Ohm meters. Resistivity measurement are conducted by inducing an electric current into the earth through two current (C1 and C2) electrodes and measuring the resulting voltage at two potential electrodes (P1 and P2). The apparent resistivity (pa) value can be calculated based on the current (I) and voltage (V).

\[ \text{pa} = k \frac{V}{I} \] (1.0)

k represented the geometric factor that depends on the arrangement of four electrodes. Imaging depth of ERM method is dependent on the spacing between electrodes. Greater depth is achieved by increasing the electrode spacing. The total length of electrode array also plays role in resulting greater imaging depth. The overall subsurface resistivity also affects the imaging depth with highly resistive ground tending to decrease the depth after inversion. In accordance to [6], the resistivity values of groundwater vary in range from 10 to 100 ohm-m depending on the concentration of dissolved salts contain as refer in Table 2. However, the overlap value resistivity of different classes of waters was depending on several factors such as porosity, degree of water saturation and concentration of dissolved salts.

Table 2. Resistivity values of some types of waters [6].

| Type of water                                      | Resistivity (ohm-m) |
|---------------------------------------------------|---------------------|
| Precipitation                                     | 30 – 1000           |
| Surface water in area of igneous rock             | 30 – 500            |
| Surface water in area of sedimentary rock         | 10 – 100            |
| Groundwater in area of igneous rock               | 30 – 150            |
| Groundwater in area of sedimentary rock           | > 1                 |
| Sea water                                         | 0.2                 |
| Freshwater                                        | 10 – 100            |
| Drinking water (max. salt content 0.25%)          | > 1.8               |
| Water for irrigation and stock watering (max salt content 0.25%) | > 0.65               |
2.1 Electrode Configuration

In electrical resistivity survey, high resolution, reliable and good imaging are depending on choices of electrode configuration or normally known as array [7]. Several studies have been conducted regarding the performance of various array. In data acquisition, there are many types of array to be used. Wenner, Schlumberger, Dipole-dipole, Pole-pole and Pole-dipole were the common array used in investigating the underground layer. The array configuration has a substantial influence on the resolution, sensitivity and depth of investigation. Table 3 shows the characteristics of each array configurations in terms of sensitivity of array to horizontal and vertical heterogeneities, depth of investigation, horizontal data coverage and the signal strength [8]. Each of the array has its own specific advantages and limitations. In choosing appropriate array several factors are considered such as depth of object, type of heterogeneity to be mapped, vertical and horizontal changes of the subsurface and signal strength. However, the objective of the survey is the main factor to be considered. [8][9] Emphasizes that on certain cases the use of various configuration can improve the different reading characteristics of the subsoil and lead to a better interpretation.

Table 3. Characteristics of array configuration [8].

|                  | Wenner | Schlumberger | Dipole-dipole | Pole-pole | Pole-dipole |
|------------------|--------|--------------|---------------|-----------|------------|
| Sensitivity of the array horizontal structures | ++++   | ++           | +             | ++        | ++         |
| Sensitivity of the array vertical structures  | +      | ++           | +++          | ++        | +          |
| Depth of investigation                          | +      | ++           | +++          | +++       | +++        |
| Horizontal data coverage                        | +      | ++           | +++          | +++       | +++        |
| Signal strength                                 | ++++   | +++          | +            | +++       | ++         |

The labels are classified (+) to (++++) equivalent at poor sensitivity to high sensitivity for the different configurations.

2.2 Factors Influence ERM Value

The electrical resistivity is based on the principle that the earth material is being tested acts as a resistor in a circuit. After electrical current induced into the ground, the ability of a material to resist current were measured. Various of earth materials could be distinguished by using this application since various of earth materials exhibit characteristics of resistivity value. There were several factors that affected resistivity values of earth materials. The ground resistivity value is influenced by various factors such as density, moisture content, void ratio, grain size fraction and porosity [8].

ERM capable in imaging changes of apparent resistivity with depth locally and to detect the water saturated clay, which identified as lower resistivity zone. This application has theoretically stated that water content in subsurface materials has a close correlation with the electrical conductivity [10]. Thus, the resistivity value will change or constant according to water content in the materials.

Degree of fractures is the common factors that influence resistivity values. The fractures are commonly filled with groundwater. The greater the fractures the lower the resistivity value of the rock layer [11]. The statement could be understood, example by resistivity of granite that varies within 5,000 ohm-m for wet condition to 10,000 ohm-m in dry condition. Resistivity value of these rocks will be low to moderate, which from few ohm-m to less of hundred ohm-m when saturated with water. Soils that located above water table are much drier and have a higher resistivity value of several hundreds to thousand ohm-m. While, soils below the water table generally gives resistivity value of less than 100 ohm-m [12]. Other factors such as density, porosity, pore size and shape of the aquifer, quality of water encountered in the aquifer and temperature of subsurface environment [12] also influence the resistivity value.
3. Groundwater Exploration using ERM

The application of geophysical method offers a better way than most conventional method in groundwater exploration. Well drilling is one of the conventional method which applied a direct way in exploring subsurface groundwater system, however the cost is very expensive. Sufficient numbers of boreholes are required to be drilled to describe the depth and constituency of various geological formation. Geophysical method was originally developed for oil and mineral exploration, as water becomes more valuable and scarcer this technique was also applied for groundwater exploration and had improved the understanding of groundwater resources. ERM has been proved to be the most effective technique in mapping groundwater resource as groundwater movement and existence are largely localized and hard to determine [13]. With a support borehole data and interpretation from the resistivity imaging obtained, the reliable information regarding groundwater can be produced. To locate the groundwater application of electrical resistivity imaging method is the common technique utilized nowadays. In Malaysia, application of ERM had already implemented as an alternative tool to solve various problems, especially in civil engineering fields and research. Most common problem in the field was subsurface failure and underground contamination. Successful implementation of this tools had help especially engineers to identify the sources of failure in the subsurface thus prevent damage for surrounding structure and material investigated [14]. The occurrence of groundwater resources in an area is defined by various geological factors that includes structure, geological sequences and stratigraphic distributions of hydrological units [15]. Recharge rate is also an important factor in determining the occurrence of groundwater in an area. Groundwater recharge in an aquifer occurs through the following mechanism: direct infiltration of rainfall, infiltration through river and lateral subsurface inflows commonly through fractures. Various geophysical techniques are currently being applied to assess and explore groundwater. However, ERM is the most powerful and cost-effective techniques in groundwater studies. This is due to the close relationships between the electrical properties and some of hydrogeological properties of the aquifer [15]. Many researchers in Malaysia had applied geophysical technique especially ERM for exploration of groundwater.

The rapid of urban development and growing of population for public, domestic, commercial water supply have caused the local authority to utilize groundwater as an alternative source for water supply. Study at Banting, Selangor proposed the application of 2D resistivity to delineate the groundwater aquifer for extensive exploration for groundwater resources as well as mapping the thickness of aquifer and bedrock in this area. The geological setting of study area is formed by silt and sands as well as peat and clayey materials as illustrate in Figure 1. During data acquisition, Wenner electrode configuration was chosen as it provides good vertical resolution and clear image for groundwater and sand-clay boundaries as horizontal structures. In addition, the array also provides dense near surface cover of resistivity data. Interpretation of this techniques clearly shows that the thickness of the aquifer varies between 10 m to 30 m and certain areas shows up to 45 m depth depending on the length of the survey line. Based on the result obtained, it indicates that the image interpret is similar to well logs. Thus, it demonstrates that the resistivity is an effective tool for imaging the thickness of groundwater aquifers and mapping or bedrock in condition of tropical zones with relatively shallow depth [16].

Figure 1. Subsurface image at Banting, Selangor [16].
In Negeri Sembilan ERM was conducted to find the source of mineral water. 2D resistivity is very practical in the study as it can provide information that required by authorities. The authorities requested that sources of groundwater should be at least 100 m deep for approval and commercialization purposes. ERM is known for time and cost effective as it provides cross section in two-dimensional compared to conventional drilling method that provides data only at the point of drilling. A suitable location for proposed well was located at 40 m from the centre of the measurement to a minimum depth of 100 m. **Figure 2** illustrates the subsurface image of the study area. Based on Figure 1, fresh groundwater with resistivity value of that less than 100 ohm-m (low resistivity values) can be seen in between granite bedrock (high resistivity values) which indicates that the water seeps through the fractured bedrock and accumulated there.

![Figure 2. Subsurface image at Negeri Sembilan for groundwater exploration](image1)

Study at Beriah landfill site, Perak by [17], applied Schlumberger array to obtain more information on finding out some hidden water and to explore the location of storing underground water. Beriah landfill is situated in area that dominant with recent alluvium deposits that consist of clay, silt, sand and gravel. Six (6) resistivity lines were carried out and results from RES2DINV shows that most of the survey lines were dominated by low resistivity zone. **Figure 3** shows low resistivity values of less than 80 ohm-m may indicate sand layer and potentially good for groundwater presence. At the depth of 5 m, the low resistivity is due to the leachate drain and pond located nearby the survey line, while high resistivity value is due to compacted soil of the road. Thus, this application had successfully indicated groundwater potential at the landfill area.

![Figure 3. Resistivity profile at Beriah landfill, Perak](image2)

The resistivity method study by [18] also was used in studying the effect of environmental impact and physical changes on coastal-area salinity for both soil and groundwater at Sungai Besar, Selangor. The environmental impact causes from the previous flooding of the shore by seawater had resulting in severe coastal erosion in the area. 2D resistivity technique was used as to evaluate the extent salinity to soil and groundwater. The resistivity data of subsurface profile for the survey line were calculated through inverse modelling, with support of borehole data which shows the lithology
information of: Quaternary alluvium sediments that more than 80 m deep consists of alternating layers of sand, silt and clay. Based from the 2D resistivity image in Figure 4, it indicate that area of saline plume with resistivity value of less than 0.2 ohm-m was found scattered on top of the impermeable layer of marine clay. Profile image L₁ obtained shows that the saline plume spots had penetrate the first confined aquifer at depth of 18 to 35.40 m below ground surface while for image profile L₂ the saline plume had penetrate until 20m from ground surface. Result from resistivity image also shown that the second confined aquifer has not been affected by saltwater intrusion. The result from this study suggested that the salinity of groundwater aquifer causes probably due to ancient seawater flooding that has long seep through sediments, instead of direct from seawater-intrusion.

Figure 4. Resistivity profile image for (a) line L₁ and (b) line L₂ at Sungai Besar, Selangor [18].

Study between resistivity and groundwater was conducted at Sg. Udang, Melaka for to detect and delineate subsurface water resource [19]. The results obtain were used for developing groundwater model which will act as guidance in designing groundwater monitoring network. With a clayey silt surface soil, Wenner electrode configuration was carried out using ABEM SAS 1000 and electrode selector system ES464. Two different electrodes spacing were applied with 2 m and 5 m spacing as to obtain precise result. The data from resistivity method for both spacing shows similar pattern of resistivity distribution but 5 m gives deeper penetration as illustrate in Figure 5. This method locates that the soil materials is inhomogeneous as the unsaturated top soil layer has a medium to high resistivity (1,100 to 2,600 ohm-m) at the thickness about 4 m. While below 4 m the saturated zone shows medium resistivity value of (750 to 1,100 ohm-m). Between the depths of 20 m to 28 m the water saturated zone is identified as low resistivity zone with ERV that less than 80 ohm-m the groundwater level was measured at 8.73 m below ground level. The unsaturated layer is normally characterized by high resistivity values whereas the water saturated layer shows zone of low resistivity. However, these layers are not clearly divided due to the inhomogeneous properties of the soil material.
[20] and [21] conducted the studies on the application of ERM to find the potential groundwater at Kerian Scheme, Perak. Study at Selinsing canal, Kerian irrigation scheme applied ERM to define the depth of groundwater aquifer from the subsoil, water table and depth of bedrock as well to situate the location site for well. This technique is important in preliminary steps of any groundwater investigation, the greater emphasis is required as to planning and managing of most favourable utilization of water resources. ERM was conducted at three different location sites at Selinsing 1, Selinsing 2 and Selinsing 3 assisted by borehole data for comparison purposes. Schlumberger array with 10 m constant electrode spacing was used in this study for deeper penetration to delineate the location of groundwater storage. The result obtained shows that the thickness of the aquifer is about 5 to 10 m at the depth of 30 to 70 m with mostly in clay layer. The interpretation of the 2D resistivity profiles from the three sites indicate that the groundwater layer has the resistivity value of less than 100ohm-m. Errors and negative readings occur during data acquisition is basically due to dried condition. Table 4 below shows other application of ERM in several studies.
Table 4. Summary of ERM in various aspects of groundwater studies.

| Year | Ref. | Method | Propose of study | Finding |
|------|------|--------|------------------|---------|
| 2016 | [22] | Dipole-dipole array is used as it is excellent for interpreting complex structures and provide high resolution data | Groundwater contamination monitoring | The ERM had successfully identify the contamination zone as it were lower than that clean zone due to ions or molecules in groundwater. The resistivity boundary between contaminated and clean zone observed by 2D resistivity was approximately 100 ohm-m. |
| 2015 | [23] | Wenner electrode array configuration | Groundwater exploration | ERM has provided a clear view of the lithological, weathering profiles and geological structures favourable for groundwater exploration and development in the study area. |
| 2014 | [24] | Wenner and Gradient array were chosen due to good vertical resolution, less sensitivity to noise and better lateral coverage. | Groundwater pollution | The contribution of resistivity imaging indicates the presence of hydrocarbon with anomalously high resistivity <15,000 ohm-m in most parts of study area due to leakage from several pipelines or activity of vandals. |
| 2010 | [25] | Wenner-Schlumberger is used as it is moderately sensitive to both horizontal and vertical structures | Groundwater exploration | Three survey lines with length of 400m for each survey line were setup during data acquisition. The existence of groundwater based on resistivity value from the interpretation is about 10 to 100 ohm-m. Meanwhile, the result also shows that the subsurface in this study area is made up of alluvium and clay. The maximum depth obtains by using this array is 77m. |

4. Conclusion

Based on all the case study presented, it shows that the application of ERM had successfully helped engineers in mapping several civil engineering interests and problem, especially during preliminary stage in groundwater exploration. The groundwater (1-100ohm-m) can be easily detected with supported by borehole data and geochemistry information as this technique is efficient in term of cost, time and data coverage. Besides, the types of array chosen during data acquisition is important in obtaining precise result based on the main objective of the study. The theory and application of resistivity method should be explored in depth by engineers to obtain a reliable information. To improve understanding of this application, guidance and help from geophysicists are required as this field was their expert.

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