Characterization of aquifer system using electrical resistivity tomography (ERT) and induced polarisation (IP) techniques

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Abstract. Groundwater plays a major role as an alternative freshwater resource for irrigation and industrial purposes. This study aimed to characterize the subsurface of aquifer systems in Teluk Intan district, Perak, Malaysia using Electrical Resistivity Tomography (ERT) and Induced Polarization (IP) methods. The horizontal profiling (TL1 and TL2) was conducted at a length of 400 m. The estimated depth is 150 m below ground level (b.g.l.). An ABEM SAS 4000 Terrameter and ABEM LUND ES464 Imaging System were applied to create a resistivity pseudo-section using polar-dipole configuration. The collected geo-electrical data was interpreted using RESIST software with partial curve matching and computer iteration. ERT and IP survey profile results were validated with in-situ borehole data from borehole 2 (B2). Eleven samples of soil profile were collected at depth from 5.6 m to 61.2 m, with average percentage of sand, silt and clay are 93.77 %, 5.78 % and 0.02 %, respectively. The geology of subsurface settings is the key factor in determining the aquifer system characterized by interlayer sand-silt sequence indicating the saturation zone of aquifer underlain by shale at the bottom. Further study on hydraulics perspective is important to understand the overall capacity of the aquifer.

Keywords: Aquifer system; sub surface profiling; groundwater; electrical resistivity tomography (ERT); induced polarisation (IP)

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1. Introduction

Groundwater is a critical resource for the environmental system and human consumption [1]. The availability, quantity, and quality of groundwater mainly depend on aquifer characteristics, natural processes, human activities, and underlying geological formations [2,3]. Groundwater is stored either in alluvial formations (clay, silt, sand, gravel, sandstone, limestone, or unconsolidated substances, etc.) or hard rock formations such as igneous and metamorphic rocks. UNESCO has estimated that the worldwide water demand will increase by 20 % and up to 30 % (4600 km³ per year) in 2050, particularly in three sectors namely, agriculture, household, and industry [4]. In Malaysia, large quantity of fresh water demand is increasing too i.e. for rice cultivation and drinking water [5,6]. Given the fact that Malaysia is water abundance region, the potential of groundwater resource is not...
fully utilised currently due to surface water remain as the major resources (97 %) for industries, agriculture, and other human consumption in Malaysia.

Previous studies also reported that surface water quality is decreasing in Malaysia due to a growing number of contamination sources such as palm oil mills, sewage treatment plants, irrigation practices and other industrial applications [6,7], hence it will limit the accessibility and availability of surface water particularly for irrigation purposes. In this context, the groundwater was identified as one of Malaysia’s alternative water supplies [8]. Various methods have been performed to study the hydraulic properties of aquifer system i.e. nuclear magnetic resonance, multilevel slug tests, pumping tests, grain size distribution from core samples, and single-borehole measurements in completed boreholes, as flow meter measurements [9,10]. Furthermore, the geophysical information of the subsurface characteristic is useful as an alternative approach to wildcat drilling [11], hence provide better decision making in determine the best potential well for drilling.

The geophysical investigation is essential to avoid drilling abortive wells, and it leads to addresses failing boreholes problems effectively because they provide the knowledge of sub- aquifer boundaries and subsurface lithology properties of a specific location [12–14]. In fact, geophysical is often plagued with uncertainties and ambiguities in interpretation, and it provides a cost-effective and rapid way of obtaining continuous information from near-surface [15–17].

Electrical resistivity tomography (ERT) or (electrical resistivity imaging Induced polarization and (IP) methods have been mainly used in the geophysical survey to determine the subsurface profiles and resistivity of substances [18,19]. ERT and IP methods are based on a current flow by the subsurface medium which is comprised of fissures and pores of soils/rocks entirely or partly filled with water and layers of various resistive materials [11]. Resistivity is a parameter measured in the unit of ohm meter (Ω.m) which determines the resistivity of a particular substance to the electrical current flow. Electrical current is produced in the ground, the possible difference is measured, and resistivity can be determined.

ERT has been used for different purposes such as monitoring of pollutants, hydrogeology, volcano imaging, engineering geology (studying and tracking leakage in dams and embankments), agricultural fields, etc. [18]. In such cases, ERT is a suitable technique and helps to view the electrical characteristics of the subsurface features because groundwater and soil moisture are mostly electrically conductive [20]. The calculated resistivity through the ERT method is influenced mainly by the amount of water in the soil and by the concentration in porous media of dissolved solids [17]. ERT is limited to mapping the medium electrical resistivity, while the IP method provides the ability to distinguish specific physical characteristics of the subsurface which is known as chargeability.

The IP method has been developed especially for the prospecting of minerals [21] IP survey is a helpful technique to map unconsolidated sediment layers of lithological material [22]. It also provides an essential parameter that can be utilized for the results interpretation by geophysical methods to resolve ambiguities. Nonetheless, due to the heterogeneity of rock and soils at the local scales in which the polarization process operates, the interpretation of IP parameters in subsurface formations may be complex [23].

The objective of this study is to characterize the aquifer system in the subsurface lithology of LabuKubung, TelukIntan district, Perak, Peninsular Malaysia. A combination of ERT and IP methods is used to investigate the subsurface profile and potential groundwater resources based on resistivity and chargeability values.

2. Materials and Methods

2.1. Study area
The study area is in the tropical region of Peninsula Malaysia, a part of the TelukIntan district in the Perak state; its name is LabuKubung, as shown in Figure 1. The approximate coordinates are $4^\circ \ 7' \ 18.35'' \ N$ and $101^\circ \ 2' \ 0.67'' \ E$ at an average elevation of 39 to 41 meters above mean sea level
(Figure 1). The general topography of the study area is naturally flat plain and it is surrounded by paddy fields and main roads [24]. This study area receives approximately 2450 mm rainfall per year. The average temperature between 23.5 °C (minimum) and 33.5 °C (maximum) with average relative humidity varies from 64 % to 94 %. The dry season lies between June to August and the wet season lies from March-May and October-December.

2.2. Geology and hydrogeology

The geology of Peninsular Malaysia is distinguished through three longitudinal north-south belts such as the Eastern Belt, the Central Belt, and the Western Belt (Figure 2). These belts have been associated with the differences in stratigraphy, magmatism, structure, geological evolution, and geophysical signatures [25,26]. Perak state is situated in the Western belt and consists of continental sequences such as quaternary deposits, sandstone, siltstone, shale, metamorphic rocks, and unconsolidated formations, as well as ranged from Cambrian to Quaternary period [27,28]. Batchelor [29] has been described as the stratigraphy of the study area lies in the Gula formation of the Holocene age (480±120 year). Hassan [30] reported that this formation has been divided into five members based on localities such as Bagan Datoh, Teluk Intan, Matang Gelugor, Port Weld, and Parit Buntar. Labu Kubung area is located in Bagan Datoh member, which is mainly composed of clay, silt, and sand deposits, as well as represents shallow marine, estuarine, and offshore environments [30].

The alluvial aquifers can be found along the coastal region of the Western Peninsular Belt with potential range from 30 to 50 m$^3$/d [24] while the central belt depicts hard rock aquifer potential. Alluvium soils are deposited from surface water which normally occurs in a discontinuous and irregular formation on the flood plain in this area [24]. Thus, due to low cementation between grains, most alluvial formations demonstrate high porosity [31,32]. Teluk Intan area consists about 15 m thickness of alluvium soils [24]. As well, studies showed that aquifers with meta-sedimentary, sedimentary and igneous rocks settings have the capacity for pumping with average well yields range from 10 to 40 m$^3$/h [33].
Figure 1. The map is showing the study area of Teluk Intan, Perak, Malaysia.
2.3. Field experiments

2.3.1. ERT and IP surveys

The two-dimensional (2D) ERT and IP surveys were used in this study. The 2D process is applied as a combination of assessment of both sounding and profiling that examines subsurface lithological objects by changing resistivity horizontally in order to obtain the information simultaneously regarding resistivity in a horizontal and vertical direction [14]. ERT is a cost-effective, rapid, and flexible method for obtaining essential information for groundwater exploration planning and the evaluation of shallow subsurface profiles. Further, ERT method investigates the ground resistivity distribution that can vary with the content of water and the lithological material [23]. The resistivity distribution in ground will provide depictions of subsurface heterogeneity or homogeneous. The subsurface is typically heterogeneous in the study area so that the resistivity observed is apparent for ERT surveys. The greater the resistivity contrast, the easier to detect and recognize the characteristics of the various materials. Moreover, inverse modelling (inversion) is applied to measure the true resistivity distribution to produce a model based on apparent data [34]. From a resistivity survey, a measured resistivity model is produced. By using RES2DInv software or similar, with inversion technique of robust or smoothness constraint, a calculated resistivity model is then produced. Both of these models will be compared of their correctness or similarity hence producing the inverted model (this will show a true resistivity value that can be compared to the geological resistivity table) and error shown means the differences between the measured and calculated model that the inverted model come out with [35]. The resistivity of earth materials is influenced by the metal content in the rock, porosity, clay content, permeability, and pore saturation degree. Thus, the resistivity value of various geological materials is shown in Table 1 and Table 2.

Figure 2: The map is showing the geological formation of the study area.
Table 1. Resistivity values of various types of waters [36].

| Types of water                                      | Resistivity (Ω.m) |
|----------------------------------------------------|-------------------|
| Precipitation                                      | 30 – 1000         |
| Surface water, in areas of igneous rock            | 30 – 500          |
| Surface water, in areas of sedimentary rock        | 10 – 100          |
| Groundwater, in areas of igneous rock              | 30 – 150          |
| Groundwater, in areas of sedimentary rock          | > 1               |
| Sea water                                          | ≈ 2               |
| Drinking water (max salt content 0.25%)            | > 1.8             |
| Water for irrigation and stock watering (max salt content 0.25%) | > 0.65           |

Table 2. Resistivity values of some types of soils [37].

| Type of water | Resistivity (Ω.m) |
|---------------|-------------------|
| Alluvium      | 10 – 800          |
| Sand          | 60 – 1000         |
| Clay          | 1 – 100           |
| Groundwater   | 10 – 100          |
| Sandstone     | 8 – 4 x 10        |
| Shale         | 20 – 2 x 100      |
| Limestone     | 50 – 4 x 100      |
| Granite       | 5000 – 1000000    |

IP is the earth's ability to hold electric charge overtime or chargeability. The IP effect estimates the soil capability to be polarized when it is influenced by an electric field, which implies energy is reversibly stored in the soil during polarization. The IP measurements were conducted in the time domain for this research. IP surveys are performed by transfer of current to the ground, whereas the potential difference is estimated to evaluate the resistivity. The ground's potential decay is estimated again in windows after the current is shut off.

The chargeability measured the voltage decay curve, and the proportion of the residual voltage amplitude was determined with the DC potential immediately after the current shut-off. The higher the chargeability, the longer the charge is held; the chargeability decays over time, typically a few seconds but sometimes up to minutes, and will eventually disappear. IP is a resistivity derivative; however, the first measure of the resistivity and IP is calculated at the end of a resistivity cycle for IP measurements. Thus, the chargeability value for various geological materials is shown in Table 3.

Table 3. Chargeability value for different geological material [37].

| Material type | Chargeability (m.sec) |
|---------------|-----------------------|
| Groundwater   | 0                     |
| Alluvium      | 1 - 4                 |
| Gravel        | 3 - 9                 |
| Schist        | 5 - 20                |
| Sandstone     | 3 - 12                |
| Argillite     | 3 - 10                |
| Quartzite     | 5 - 12                |
2.3.2. Electrode arrangement and instruments

In the field measurement, the ERT technique was applied with the multi-electrode electrical imaging system such as ABEM Lund Imaging System using various layouts. Furthermore, it is an automated imaging system to process, collect, and display resistivity based on the variation in conductivity between the geological rock formation and the adjacent substances. This imaging system is a new technology recently developed to examine the underground properties of regions with complex geological formations. The use of other techniques, including resistivity soundings, is not productive.

The resistivity imaging system defines the density, the electrodes' configuration, and the amount of data to be collected. Also, it can estimate a range of constant separation traverses by growing the electrode spacing. Because the separation increases the penetration of more depth, the contoured vertical image of apparent resistivity measured indicates vertical and lateral changes in apparent resistivity across the section. Moreover, ABEM Terrameter SAS (Signal Averaging System) 4000, electrode selector LUND ES464, and other equipment have been used to build up a resistivity pseudo-section, as shown in Figure 3.

A computerized device is used to select the active electrodes for each measurement automatically. The general principle of using an ERT device typically with the ABEM Terrameter with 62 electrodes for making a pseudo-section resistivity is given in Figure 4. Whereas SAS meter automatically records consecutive readings and displays the average results on a meter screen simultaneously. Moreover, the SAS-4000 Terrameter can work in three mechanisms: a) resistance measurement (mode of resistivity survey), b) voltage measurement mode, and c) induced polarization. Moreover, the direct current (DC) has been passed into the surface since DC may penetrate more in-depth than the alternative currency (AC). Also, the device includes four steel rods and two electric cables roller of 100 m (two rollers in each set). One pair has been used to transmit electric current into the ground, and the other to calculate the potential difference. Further, the voltage/current (V/I) ratio is automatically measured and recorded on the meter screen. The various types of electrode arrays are used to investigate the electrical resistivity, such as Schlumberger, Wenner, dipole-dipole, polar, pole-pole, and pole-dipole [38]. However, the pole-dipole configuration has been applied in this study to acquire the resistivity data (Figure 4). All measurements have been collected stacked twice in the field in order to assist the quality control as well as the flagging of erroneous data. During the survey, resistivity data were
obtained from the polar-dipole array configuration with a remote-pole positioned at an equal "infinite" distance. Figure 4 below showed the equipment for the resistivity survey.

Figure 4. (a) The diagram shows the general measurements for pseudosection development (modified after Hasan et al. [39], with the current electrode C1, the remote electrode C2 at infinity (∞) and the potential electrodes P1 and P2, (b) the principal schematic for ERT and IP measurement using a pole dipole electrode configuration, while V is the voltage, I is current, A is the current electrode, B is the remote electrode at infinity (∞), and the potential electrodes denote M and N.

2.3.3. Resistivity data processing and acquisition
The present study has been performed for the data collection by applied 2 ERT and 2 IP survey lines, whereas the names given for survey lines as TL1 and TL2, as mentioned in figure 1. Further, 2 survey lines were conducted to the length of 400 m with an electrode interval of 5 m, as well as estimated depth of each survey were 150 m. The outer electrodes have been utilized for current and were placed on the earth’s surface with 62 electrodes at a distance of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, 165, 170, 175, 180, 185, 190, 195, 200, 205, 210, 215, 220, 225, 230, 240, 245, 250, 260, 265, 270, 275, 280,
285,290,295, 300, 305, 310,315, 320, 325, 330, 335, 340,345, 350, 355, 360, 365, 370, 375, 380, 385, 390, 395, and 400.

The ERT and IP surveys data were obtained subsequently exported to RES2DINV compatible file formats in order to carry out the inversions with the software developed by Loke [40]. The 2D model used by the inversion process consists of a number of blocks having their distribution and size automatically generated by the program. This model is designed to evaluate the resistivity of blocks, creating an apparent resistivity pseudosection that agrees with the actual measurements, which is a function of the electrode array. The depth of the bottom row of blocks is set to be approximately equal to the equivalent depth of investigation. The thickness of the first layer is generally set to about 0.6 times the electrode spacing for the pole-dipole arrays. A correction is applied to the resistivity and IP data for surface topography effects during the initial loading of the files. The optimization approach effectively attempts to decrease the variance between the apparent resistivity values measured and calculated by adjusting the model block resistivity. A Root-Medium-Squared (RMS) error is used to measure this difference. The least potential RMS error model can often indicate large and unrealistic differences in model resistivity values. It may not be the “best” model from a geological perspective [41]. The most conservative technique is to select the model at the iteration, after which the RMS error is not substantially changed. The iteration RMS error was approximately 30.1 % in the ERT surveys and 6-9 RMS error in IP surveys for all inversions models. The inversion routine is used for the non-linear least-squares optimization technique and, most parameters, automatically fixed by the software.

2.3.4. Particle size analysis
In situ soil measurement was carried out with 11 soil samples from the pumped well collected in plastic boxes at a depth between 5.6 m to 61.2 m. However, nine samples were the soil samples, 1 sample was the peat, and the last sample was the bedrock as shale rock. Nine soil samples were brought back to the laboratory and dried in an oven at 40 °C for 24 hours. After dried, a Malvern Master Sizer Scirocco 2000 laser grain-size analyzer (Malvern Instruments, Malvern Company, UK) has been used for determining the particle size distributions of sediments. A soil particle size distribution was defined in terms of the calculation of percentage volume of sand, silt, and clay for the range of 2–2000 μm. The volumetric percentages were classified as clay (0-2 μm), silt (2–50 μm), and sand (50-2000 μm) based on the United States Department of Agriculture method [42].

3. Results
The geophysical survey was carried out using 2D ERT, IP surveys, and the parameter of the survey lines (TL1 and TL2) addressed in Figures 4 and 5 below. In the study area, previous studies indicated that the marine sediments describe the coastal region of TelukIntan with abundant mangrove pollen, fine to coarse sand, silt, clay, and intercalated peat layers [29,30]. The interstitial peat horizons show different phases of regression along with the environment of coastal lagoons and estuaries with sea water [12], [24], [44].

3.1. Survey line TL1
The 2D inverted resistivity model using pole-dipole array at TL1 site has been performed at a length of 400 m with an electrode interval of 5 m. The direction of the survey line TL1 was 225° N, with the starting outer electrode located at 4° 7' 22.09" N and 101° 1' 51.82" E. In contrast, the last electrode was positioned at 4° 7' 26.10" N and 101° 2' 4.41" E. TL1 line was started at a higher topographical point of 41 m and gradually decreased to the lowest point of 38 m. The resistivity profile demonstrates value range from 10-50 Ωm (Clays), 70-150 Ωm (Clay), 250-500 Ωm (alluvium and sands), and 1500-2000 Ωm (shale), suggesting the subsurface setting characterized by clays at the top followed by sand in the middle and shale as the bedrock (Figure 5).
This was confirmed by the particle size analysis, as shown in Table 4. 11 samples of soil profile were collected at depth from 5.6 m to 61.2 m (Figure 8), with average percentage of sand, silt and clay are 93.77 %, 5.78 % and 0.02 %, respectively.

### Table 4. Particle size distribution of soil samples collected from Borehole 2 (B2)

| Particle size (μm) | Alluvial formation | S1 (5.6 m) | S2 (11.2 m) | S3 (16.8 m) | S4 (22.4 m) | S5 (28 m) | S6 (36.6 m) | S7 (39.2 m) | S8 (50.4 m) | S9 (44.8 m) | S10 (56.0 m) |
|--------------------|--------------------|------------|-------------|-------------|-------------|-----------|-------------|-------------|-------------|-------------|-------------|
| 0 – 2              | Clay               | 0          | 0           | 0           | 0.21        | 0         | 0           | 0           | 0           | 0           | 0           |
| 2 – 50             | Silt               | 11.53      | 10.37       | 2.73        | 26.42       | 1.41      | 0           | 0.5         | 0.53        | 4.02        | 0.07        |
| 50 – 2000          | Sand               | 87.99      | 89.63       | 97.27       | 73.38       | 98.58     | 100         | 95.51       | 99.49       | 95.96       | 99.95       |

### 3.2. Survey line TL2

The results of ERT and IP methods in survey line TL2 site using pole-dipole array has been performed at a length of 400 m with an electrode interval of 5 m. The direction of the survey line TL2 was 225° N, with the starting outer electrode located at 4° 7' 24.98" N and 101° 1' 57.47" E, as well as the last electrode, was located at 4° 7' 14.31" N and 101° 2' 4.85" E. The resistivity values observed between the 1 Ωm to 50 Ωm at a depth of 1-10m indicate the topsoil clay layer and the ERT values ranged between 50-1000 Ωm at a depth of 10-20 m, which was interpreted as the weathered layer, as shown in Figure 6. The hard layer considered at the minimum depth of 20 m below the earth surface, where the resistivity value is between 1000-5000 Ωm. On the other hands, IP results also showed the weathered and hard rock layers in this survey, whereas chargeability values observed between 2.5 to 30 msec at a depth of 0 to 100 m in this study area (Figure 6).
4. Discussions

TL1 and TL2 survey lines provide better perspective about the subsurface characteristic of the studied area (Figure 5 and 6). TL1 line suggests three potential groundwater zones located between the distance of 50-160 m, 160-220 m, and 240-340 m at depth of 15 m, 15 m and 30 m b.g.l. (below ground level), respectively, as shown in Figure 5. However, B2 was selected for drilling due accessibility factor. Further, eleven samples of soil profile were collected at depth from 5.6 m to 61.2 m (Figure 8), with average percentage of sand, silt and clay are 93.77 %, 5.78 % and 0.02 %, respectively. The geology of subsurface settings (silt, clay, sand, some peat and shale) is the key factor in determining the aquifer system (Figure 7). The black-dashed line (TL1 survey line, Figure 5) demarcates the groundwater potential zones in the study area characterized by interlayer sand-silt sequence (Figures 7 and 8) indicating the saturation zone of aquifer [45] underlain by shale at the bottom [46]. Consequently, the interlayer sand-silt sequence or sand layers indicate the permeable beds or saturation zone may consider as an aquifer system [45], as shown in (Figure 7 and 8). Further study on hydraulics is important to understand the overall capacity of the aquifer.
Figure 8. ERT and IP results showed the high potential groundwater system and geological formations (red dashed line) in survey line TL1 (for B2).
5. Conclusion
This study performed the geophysical survey using ERT and IP techniques to investigate the subsurface profile and identify the aquifer system in LabuKubung, TelukIntan, Perak. ERT and IP results using pole-dipole electrode configuration demonstrated the sub-surface lithology of the Quaternary period, which indicated the alluvial formations of sand, silt, clay, and peat, as well as the findings revealed the low values of resistivity (70-500 Ωm) and chargeability (0-1 msec.). Two surveys (TL1 and TL2) have been performed where three potential zones in the TL1 line were identified based on ERT and IP results i.e., 50-160 m, 160-220 m, and 240-340 m at a depth of 15 m, 15 m and 30 m.b.g.l., respectively. However, the subsurface profiling at TL2 indicates high resistivity and chargeability values suggesting a hard rock system. The geology of subsurface settings (silt, clay, sand, and shale) is the key factor in determining the aquifer system, characterized by interlayer sand-silt sequence indicating the saturation zone of aquifer underlain by the shale at the bottom.

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