Petroleum and Coal

Article **Open Access**

COMBINED USE OF 2D ELECTRICAL RESISTIVITY AND SEISMIC REFRACTION IN HYDROGEOPHYSICAL EXPLORATION

Ali Abdullah Musa[1], Joel Ben-Awuah*[2, 3], Rosli Saad[4], Spariharijaona Andriamihaja[1, 3, 5]

[1] Department of Geoscience, Faculty of Petroleum Engineering and Geoscience, Universiti Teknologi PETRONAS, 32610 Seri Iskandar, Perak, Malaysia
[2] Department of Chemical and Petroleum Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, Taman Taynton View, 56000 Cheras, Kuala Lumpur, Malaysia
[3] PetroGeo Oil and Gas Consult Limited, P.O. Box MD191, Madina-Accra, Ghana
[4] School of Physics, Universiti Sains Malaysia, 11800 USM Penang, Malaysia
[5] Direction des Hydrocarbures, Office des Mines Nationales et des Industries Strategiques, Antananarivo, Madagascar

Received October 21, 2016; Accepted January 30, 2017

Abstract

The knowledge of the geometry and the physical properties characterizing the subsurface has been a challenge for groundwater exploitation. The relationship between lithological properties, electrical distribution and wave velocity was explored for this research as a means of detecting porous aquifers. The geophysical exploration involved electrical resistivity and seismic refraction surveys in parts of Selangor and Pahang areas of Malaysia. 2D resistivity conducted in these areas generated profiles from which probable positions of groundwater were identified. The field acquired resistivity data were processed with the use of RES2DINV software. For the seismic refraction method, magnitudes of wave velocity values were used to estimate depths to aquifer zones and to map the bedrock surface and subsurface structures. The high resolution seismic data that was gathered was processed and interpreted with the GREMIX program. A good hydrogeological interpretation was possible by constraining the geoelectric inversion and seismic velocities using information from known geology of the study areas. Both methods were effectively combined to ascertain the presence of fracture aquifer in hardrock complexes. Good correlation between electrical resistivity and seismic survey results confirmed the usage of integrated geophysical techniques as a reliable tool in providing useful information of the subsurface.

Keywords: Groundwater exploration; 2D electrical resistivity; Seismic refraction; Malaysia.

1. Introduction

Borehole drilling provides subsurface data directly, though expensive, localized and often inefficient. Therefore, there is the need for precise groundwater exploration techniques to reduce the high incidence of dry holes and cut the costs associated with poor groundwater production. Several geophysical techniques have been applied to groundwater investigations with some being more effective than others. Gravity and magnetic methods have been used to map regional aquifers and large scale basin features; seismic surveys have been used to delineate bedrock aquifers and fractured rock systems while electrical and electromagnetic methods have proved particularly applicable to groundwater studies, as geological formation properties such as the porosity and permeability of rocks can be correlated with electrical conductivity signatures [1]. However, as [2] points out, situations with complex geology and hydrogeology cannot be understood from a general approach, but require definite approach for specific problems.

The use of geophysical methods in highly heterogeneous media is particularly problematic because of the non-specificity of physical parameters that can explain the observations, leading to ambiguity in interpretations. For instance, a more complex task for geoelectric surveys is the search and delineation of fresh groundwater since the electrical resistivity of freshwater bearing aquifers can vary over a very wide range, and absolute resistivity values are seldom diagnostic of a particular lithology. The resistivity ranges of different earth materials overlap, thus, resistivity measurements cannot be directly related to a specific soil or rock in the subsurface without direct sampling or some other geophysical or geotechnical information. This means that instead of searching for freshwater directly, the geoelectric targets are actually resistivity divergences which represent probable lithological contrasts or environments.

Furthermore, in a given sedimentary basin, overlying alluvium or till obscures the topography of bedrock which might control the flow of groundwater. Similarly, the detection of high porosity gravel zones in the alluvium which serve as freshwater aquifers may become indiscernible during interpretation. An eventual exploration problem is the mapping of the depth to the bedrock and detection of gravel zones [3]. Hence, the electrical method will probably be unable to specify subsurface structure and resistivity distribution precisely enough for hydrogeological determinations. As a result, the determination of true resistivity for estimating hydrogeological parameters requires more accurate geophysical models which can define the true geometry of the subsurface such as radar method and seismic surveys. By combining resistivity imaging and seismic refraction geophysical methods, the ambiguity of geoelectric inversion for deriving true resistivities can be reduced, thereby allowing a more precise description of the subsurface. Correlating resistivity survey with seismic velocities can also provide reliable layering estimates. The advantage of seismic refraction is its ability to resolve three to five layers of stratigraphy and provide good depth approximations. The significant velocity contrast between alluvial material and bedrock provides an excellent environment for mapping depth to bedrock, which will improve the detection of transitions from non-saturated to fully saturated porous layers with certainty.

The objectives of this study include; identifying the position of groundwater using 2D electrical resistivity and seismic refraction, determination of true subsurface geological features, and to study the impact of combined geophysical approaches in subsurface delineation relative to groundwater content. The report seeks to prove that the accuracy of depth determination using electrical resistivity is substantially increased when combined with seismic method. Consequently, problems and limitations created by ambiguity in resistivity data interpretation and lateral inhomogeneities in the ground are drastically reduced. Meanwhile, the study adopted alluvial environment and hardrock complexes in Selangor and Pahang areas of Malaysia as case studies [4]. The phases of the geophysical survey aimed to obtain a unique insight into the effectiveness of the chosen geophysical methods for groundwater exploration in Peninsular Malaysia.

2. Data acquisition and analysis

Data acquisition and analysis are intrinsic parts that are concisely elaborated in this study. Steps were taken to ensure data analysis was carried out smoothly and systematically in order to achieve the objecttives of the research. With support from pre-field reconnaissance study, locations for data acquisition were chosen based on geographic distribution, accessibility and relevance to the study. Kalumpang, Hulu Selangor and Simpai, Pahang were chosen as the study sites for the study as shown in Figure 1.

Fig.1. Map of site locations in Kalumpang and Simpai (Google maps)

Geologically, the entire area of Kalumpang is covered by unconsolidated Quaternary alluvial sediments, consisting mainly of clay and sand; overlying metasedimentary rocks of Devonian to Silurian age, while Simpai consists of conglomerate, sandstone, shale, mudstone and limestone formations [5].

Two resistivity surveys were performed orthogonally in the Simpai area, Pahang while one resistivity line was obtained in Kalumpang area of Selangor. Seismic refraction surveys were also carried out along the same lines.

2.1. 2D Resistivity imaging

2D Resistivity imaging involved the deployment of an array of co-linear, equidistant electrodes on the surface of the ground for data collection using the most suitable protocol for electrode arrangement (Figure 1). Pole–dipole array (PDP4bru) was used because of its ability to provide a good balance between resolution and depth penetration. It can also provide more datum points for data inversion.

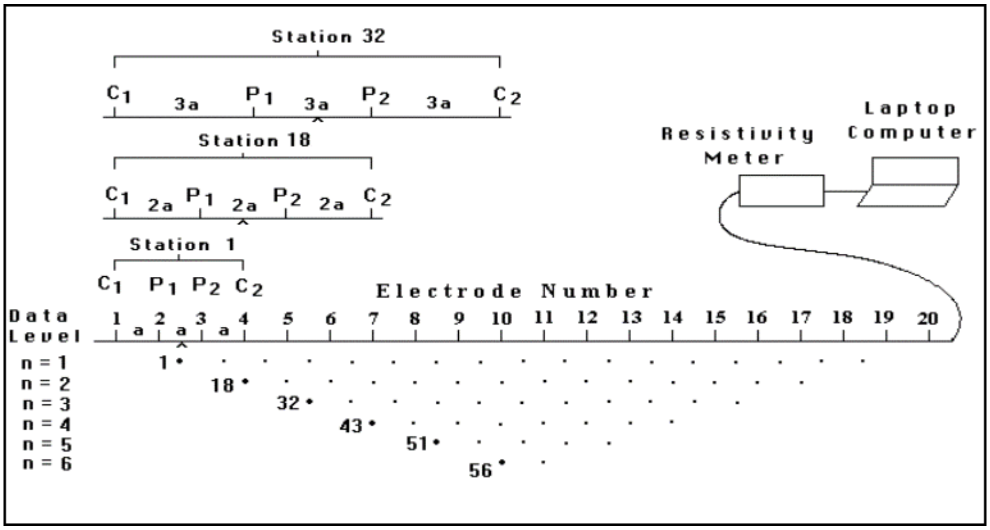

Fig. 2. Sequence of measurements to build up a pseudosection [6]

The sketch shown in Figure 2 outlines ABEM Lund imaging system in a 2D resistivity survey, with each mark on the cable indicating an electrode position. The survey utilized 4 cables comprising a 400m length. The Lund imaging cable reels 1, 2, 3 and 4 were placed on a straight line; with the outer cables 1 and 4 having 10m spacing between electrodes, while the inner cables, 2 and 3 consisted of 5m electrode spacing. The cables were then connected to the electrode selector (ES464); where cables 1 and 2 are connected to connecter-1 and cables 3 and 4 are connected to connecter-2. The cable from the selector ES464 was connected to the terrameter SAS 4000 and also to the battery. A remote cable of 400m was placed perpendicular to the survey line.

Detailed two-dimensional (2D) cross sections of the subsurface were obtained by combining the sounding and profiling data. Computer-controlled multi electrode resistivity systems reduce the intensive labour and time consumption of previous analog data analysis. The measured apparent resistivities were presented in a contoured pseudosection, which reflects qualitatively the spatial variation in resistivity in the vertical cross-section and gives an appropriate picture of the subsurface resistivity. The unit electrode spacing determines the length of the profile, depth of investigation and resolution. The contoured data was modeled by inverting the data automatically with RES2DINV.

2.2. Seismic refraction

The 24- channel ABEM terraloc MK 8 seismograph was used to acquire the seismic data. The P wave energy source consisted of a 40kg weight drop which propagated seismic wave through the ground while striking a steel plate. Each seismic refraction spread comprised a series of 24 geophones placed along the line at a set distance or geophone interval of 5m. The spread covered 115m allowing a minimum depth range of 10m depending on subsurface geological material. Several shot points were chosen for the spreads in order to provide detailed shallow data, greater depth penetration, and also to facilitate data processing. Ultimately, records were saved with SG2 format in the seismograph. The processing of the field seismic data was done with Ixseg2segy, Firstpicks and Gremix15 software packages. Seismic data processing entailed increasing the signal to noise ratio and picking out the desired signals to attain higher resolution information. Ixseg2segy software was used to filter the data while Gremix Firstpicks was used to pick the first time arrival (P waves) and upload the geometry of the seismic profiles. First breaks were picked by visual inspection of the data on the computer CRT using a cursor across the screen (Figure 3).

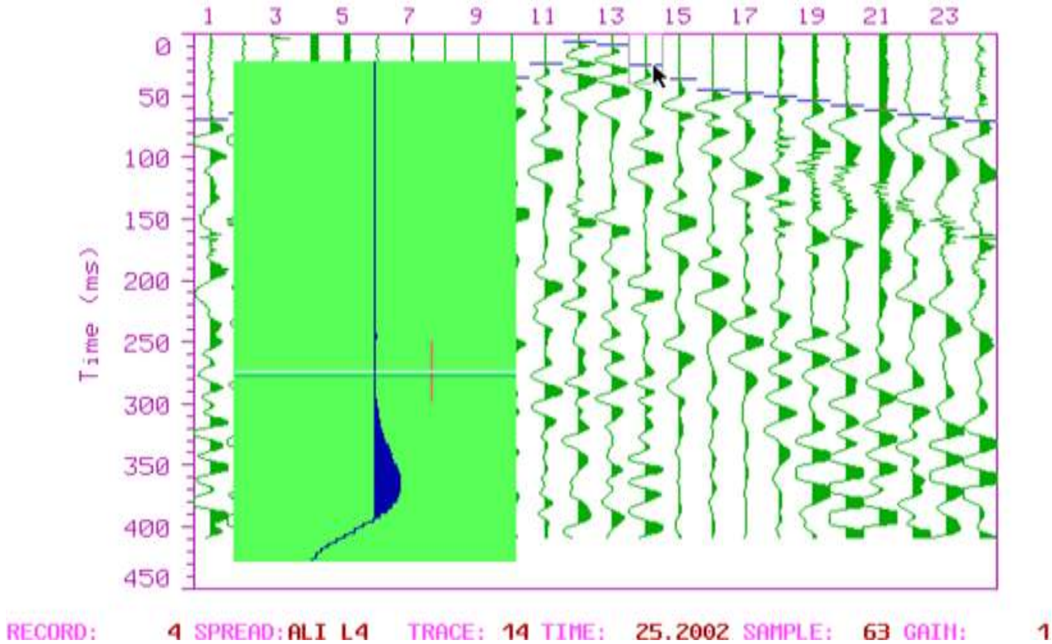

Fig. 3. First time arrivals picking using first pick Gremix software

The first arrival times of the refracted wave was then plotted versus the distance from the shot for each corresponding geophone. The input data of the program included the velocity and time intercept data from the entire shots while the output data showed depth to the top of each horizon under the shot location, and the velocity of each layer as shown in Figures 4 and 5.

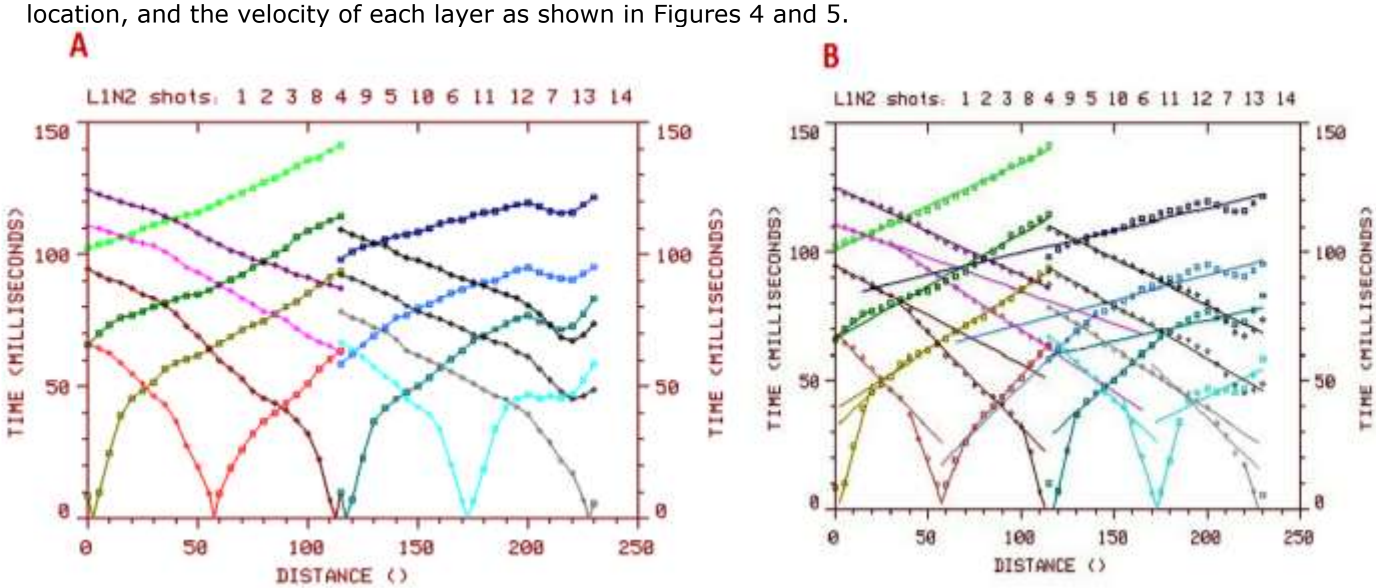

Fig. 4. A) Travel time vs. distance illustrations and B) Velocity analysis for Simpai, Pahang

Each dot and circle represents the measured response of a geophone. Its placement on the graph is determined by the geophone location in the array, and the time between energy release and the seismic wave arrival to the geophone. Measurements were taken in two directions (forward and reverse) in order to resolve dipping or inclined stratigraphy.

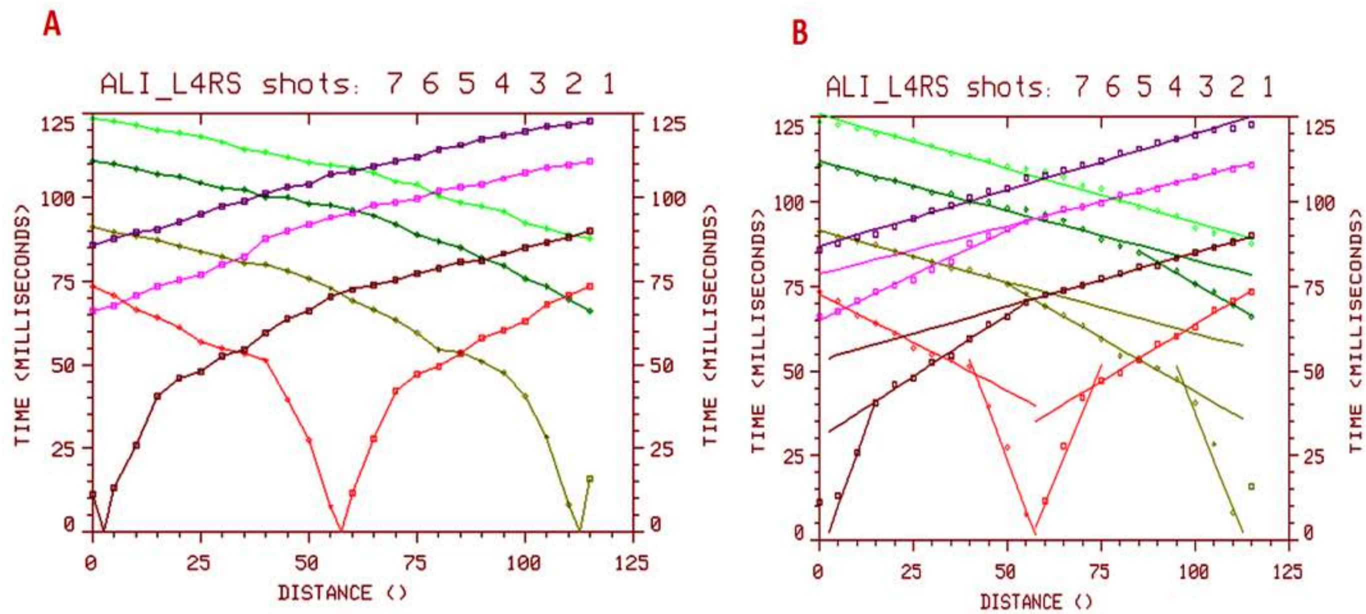

Fig. 5. A) Travel time vs. distance illustrations and B) Velocity analysis for Kalumpang, Selangor

3. Results and discussion

Subsurface resistivity is influenced by geological parameters that include; mineral and soils, fluid contents, bulk rock porosity, pore structure, fracture and presence of groundwater, while seismic velocity variations can be due to changes in water content (salinization and mineralogy), porosity, fluid saturation, soil consolidation and pressure. Knowledge of the typical resistivity values and compressional wave velocities for the different types of subsurface materials were required to derive meaningful information from the acquired geophysical data.

3.1. 2D Resistivity data

The data obtained from the electrical resistivity survey was analyzed using RES2D imaging software and RES2DINV. For data inversion, robust constraint was selected because it is less sensitive to noisy data points and its ability to depict sharp boundaries, although it gave higher apparent resistivity RMS errors when compared to standard inversion constraint. For Simpai, Pahang, the first resistivity survey line, L1 (Figure 6) shows an upper layer consisting of low conductive materials with resistivity values ranging from 150 - 1000Ω-m and a thickness of 20m. These values are a result of highly compacted and indurated sandstone, conglomerates and limestone which is consistent with the geology of the area. At a depth of 20m, a distinct geological entity is observed on the left flank of the profile, depicting contrasting resistivity values (<20Ω-m) compared to the surrounding medium. This drastic drop in resistivity values indicates a possible fracture.

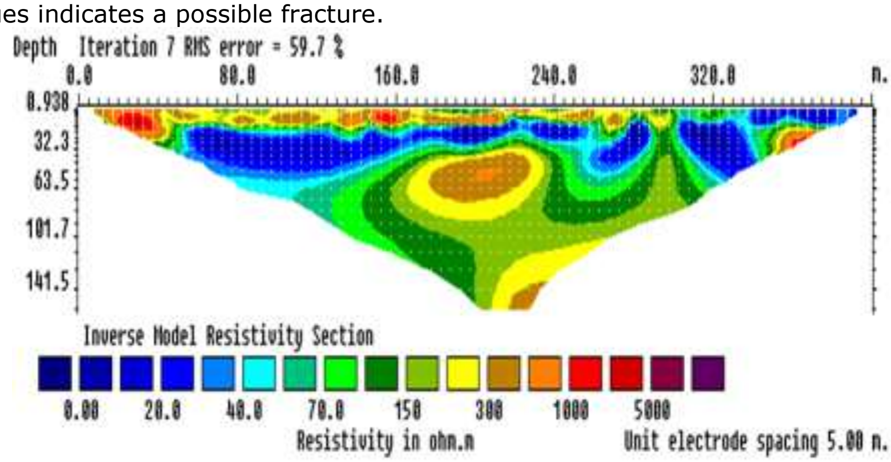

Fig. 6. Resistivity section at Simpai, Pahang (L1)

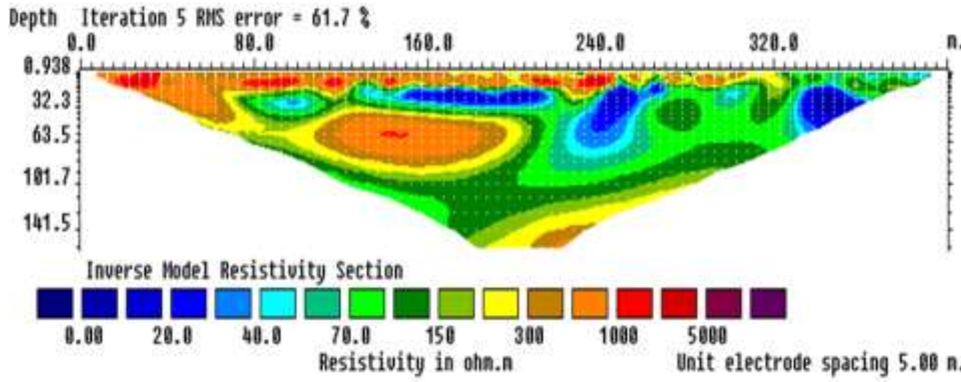

Fig. 7. Resistivity section at Simpai, Pahang (L2)

For Kalumpang Hulu Selangor, the geological interpretation of the resistivity section indicates the presence of low resistivity material of medium to coarse sand of thickness 15 - 60m at the surface, spanning over some 200m from the origin of the profile (Figure 8). Highly indurated and consolidated sandstone along with a boulder occur from about midway of the profile to an approximate depth of 100m. At the depth of 200m, the bedrock reflects high resistivity values, 5000 - 10000 Ω-m. The material is thought to be schist as confirmed by the geological history of the site area.

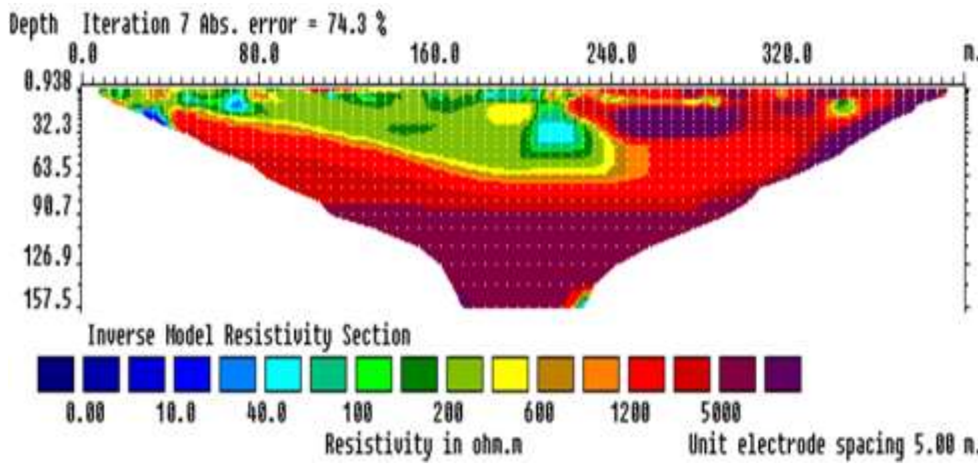

Fig. 8. Resistivity section of Kalumpang, Hulu Selangor

3.2. Seismic refraction

For the seismic refraction survey, velocities were calculated using the inverse slope of a line connecting points representing the same layer. Because distance divided by time equals velocity, the inverse of the slope of the lines equals the seismic velocity of the subsurface material. Therefore, a change in the slope represents a change in the material. The seismic geologic environment in the study region is considered a three layer case. This survey was able to resolve three separate velocity layers (V1, V2, and V3). The layers typically include the weathered zone, alluvial material, and bedrock. The weathered zone, V1 consists of unconsolidated organic topsoil layer comprising clay and friable sand which is affected by excavation activities. This upper zone has velocities of 400 - 600m/s and a thickness of less than 10m (Figure 9A). The P-wave velocity in saturated or more compacted alluvial materials is 1300 – 1500 m/s. This velocity is characteristic of the speed of sound in saturated unconsolidated sediments. The depth to bedrock throughout the area of investigation was resolved with V3.

The target for this study included searching for structures that promote aquifer parameters. The seismic survey was able to achieve this by detecting a fracture in the third layer. This layer generally consists of velocities within 1600 and 3000m/s depicting hard rock complexes, possibly a schist formation. At distance 115 – 150m, higher velocities, 3000 - 6000m/s were recorded. This drastic change in geology and increase in velocity indicates high saturation. This anomaly is clearly seen in the seismic depth section and it suggests the presence of a fracture (Figure 9B).

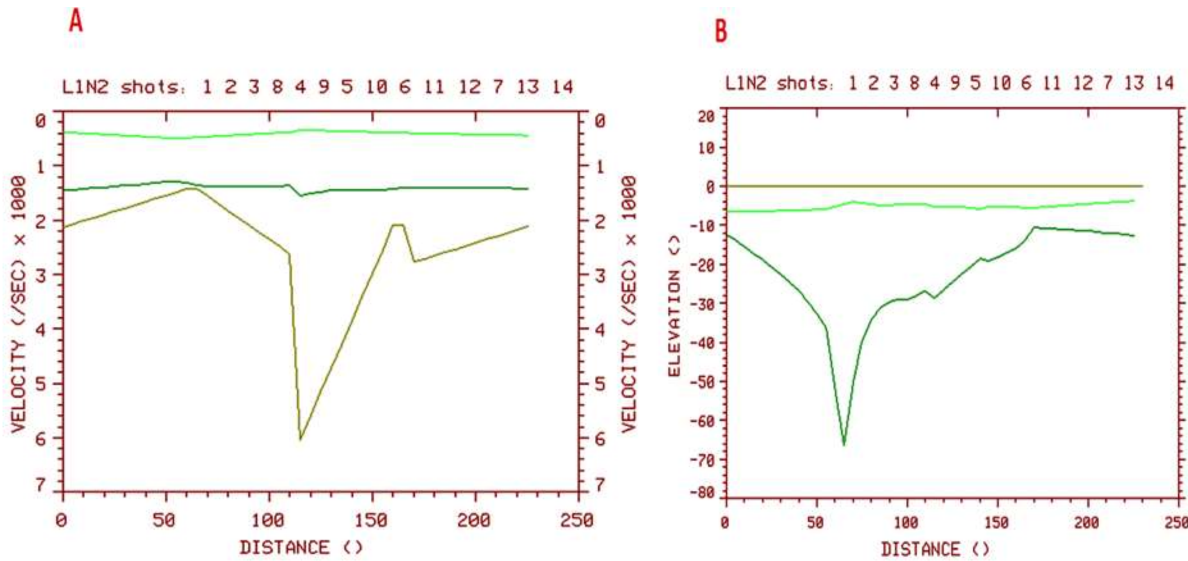

Fig. 9. A] Velocity section and, B] Depth section of Simpai, Pahang

This site location utilized one seismic line of 24 geophones and 115m, although with offset shots greater than 100m from receivers. A three layer profile was also generated for this area. The seismic refraction survey shows the transition from unsaturated to saturated formation. The first layer consist of an average velocity of 400m/s which indicates unsaturated alluvial soil, comprising clay, loose sandstone and loamy soil with a mean thickness of 7m. In the second layer, increase in velocity reflects changes in lithology and saturation. Velocity range between 1600 and 1800m/s in this layer shows increased compaction and saturation. This layer has a thickness of 19 - 28m. The third layer is the bedrock, which is possibly a schist formation with velocity of 2700 - 2950m/s (Figure 10A). There are no identifiable structures discernible in this seismic profile as observed in the depth section (Figure 10B).

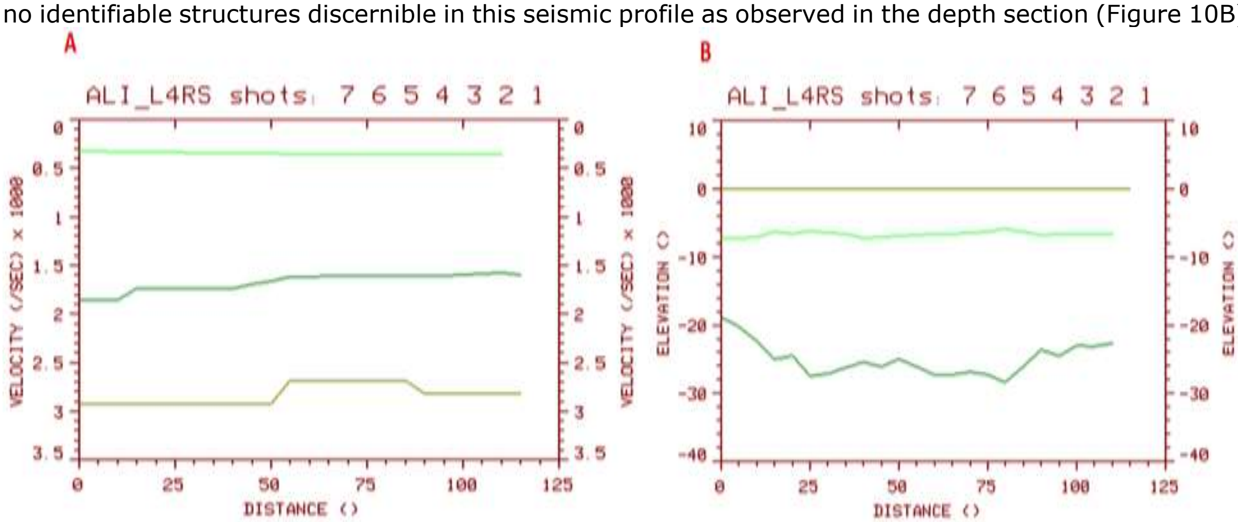

Fig. 10. A] Velocity section, and B] Depth section for Kalumpang, Selangor

3.3. Correlation of resistivity imaging with seismic refraction data

The seismic data was correlated with the resistivity pseudosections to provide a comparative study of both methods. In Simpai area of Pahang, the seismic refraction survey was conducted on the same line with the resistivity survey (Figure 11). Using the Surfer software, the seismic derived layers were superimposed on the resistivity image. The image shows positive correlations between both methods (Figure 12). Both methods were able to detect a fracture within the same lateral position and depth. The surfaces of the underground layers were comprehensibly resolved by seismic refraction. The seismic method showed distinct layering and progression from unsaturated top layer to saturated layer followed by underlying bedrock.

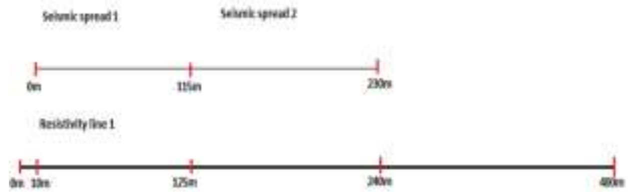

Fig. 11. Schematic arrangement of the geophysical surveys used for comparative study in Simpai

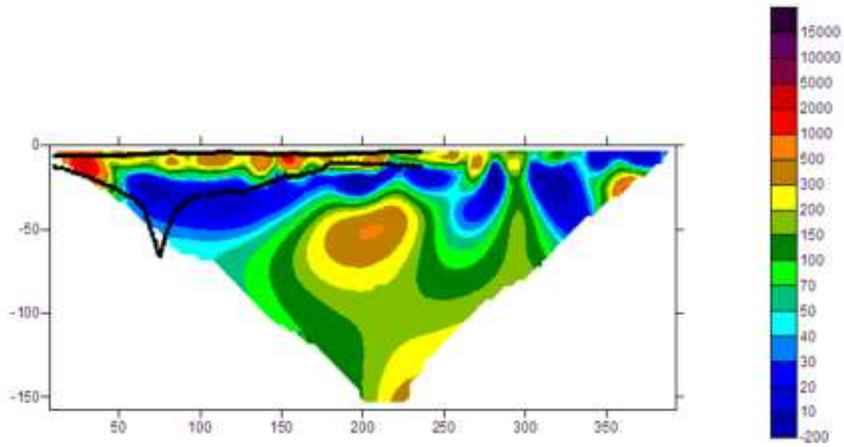

Fig. 12. Profile illustration re-iterating the correlation of 2D resistivity and seismic methods

Both surveys shared same center point, although the seismic spread provided relatively lower coverage compared to the resistivity line (Figure 13). Unlike the study done for Simpai area, the seismic line was unable to provide specific or distinct features correlatable with the resistivity section (Figure 14). However, both methods showed the transition from unsaturated weathered formation to saturated zones.

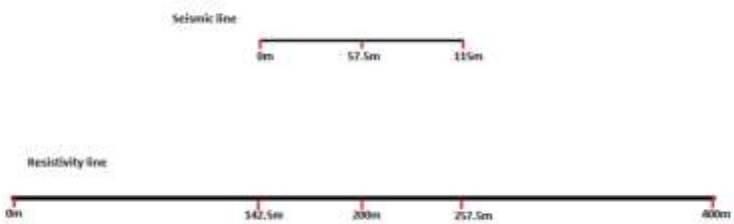

Fig. 13. Schematic arrangement of the geophysical surveys used for comparative study in Kalumpang

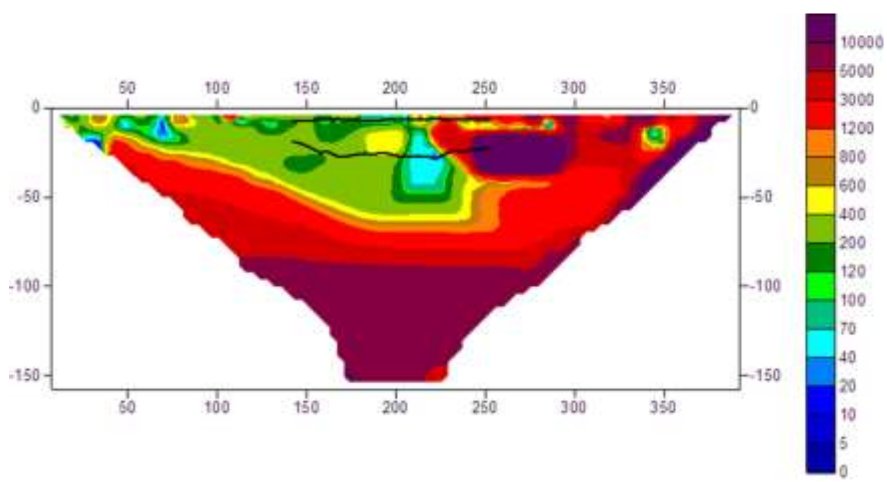

Fig. 14. Correlation of geophysical profiling and seismic refraction in Kalumpang

Pet Coal (2017); 59(1): 1-9
ISSN 1337-7027 an open access journal

4. Conclusion

Electrical resistivity and seismic refraction methods were used to describe the subsurface geology, indicate probable aquifer presence, delineate lithology and identify geological structures. The 2D Resistivity imaging allowed a distinction to be made between very highly resistive hardrock complexes, the moderately high resistivity freshwater saturated zone and the very low resistive formations, thereby providing a clear delineation of the aquiferous sand and gravel zone lying below the clay and silt formation in the study areas. The results affirmed resistivity profiling as a capable tool for providing a detailed continuous 2D image of the subsurface, which makes this technique most suitable for groundwater investigations, both for locating drilling sites and for obtaining an assessment of the general extent of the depth of weathering and the location of fractured zones, which are the principal groundwater reservoirs. The relatively accurate outlines of groundwater zones as well as the groundwater table were possible due to the precision employed in the data collection, processing and presentation of the electrical soundings. However, it was unable to provide accurate contrasts between the alluvial material and the bedrock surface.

On the other hand, the seismic method appears to be particularly well suited to the characterization of crystalline basement rocks and their weathered regolith profiles. Seismic refraction was capable of differentiating top soil from bedrock, showing graduation from unsaturated loose soil to saturated compact rock. Occasionally, this method can be helpful in determining the depth to groundwater. However, in order to be successful, the velocity of the saturated zone must be significantly greater than the overlying formation. Also, consolidated formations typically have very fast seismic velocities that are not significantly affected by groundwater, which makes the water table unlikely be detectable. Seismic velocities typically increase in unconsolidated formation; therefore if the boundary is sharp, a refraction survey will be unable to differentiate groundwater from another formation.

Nonetheless, resistivity method combined with seismic refraction proved reliable and provided certainty required before siting a borehole for water exploration. Together they were able to detect a fracture which is a viable source of groundwater accumulation (aquifer) in hardrock complexes. It can be seen that the limited resolution of structures at relatively large depths, particularly below groundwater level, can be overcome by combining electrical resistivity and seismic refraction surveys. The use of both techniques is more expensive than traditional geophysical surveying, but the additional cost may be justified when compared to the expensive use of borehole to ascertain the true situation of the subsurface. Although, it has been shown in this research, that the determination of subsurface geology and water content using correlation between geoelectrics and seismic refraction is reliable, they will always be accompanied by some ambiguity since these hydrogeological properties are derived indirectly from geophysical properties. This limitation may be reduced to some extent by the introduction of new techniques such as surface nuclear magnetic resonance (SNMR), which allows the direct determination of water content.

References

[1] Van Dongen P and Woodhouse M. Finding Groundwater: a Project Manager’s Guide to Techniques and How to use them. Technical Report: UNDP-World bank Water and Sanitation Program, 1994 World bank, Washington DC.

[2] MacDonald AM, Calow R, Nicol AL, Hop, B, Robins NS. Ethiopia: Water Security and Drought, *British Geological Survey Technical Report WC/01/02,* 2001.

[3] Fitterman DV and Stewart MT. Transient Electromagnetic Sounding for Groundwater. Geophysics 1986; 51: 995-1005.

[4] Minerals and Geoscience Department of Malaysia (2007): Status of Groundwater Abstraction and Ground Subsidence Survey at Olak Lempit, Mukim Tanjung 12, Banting, Selangor. Report No. JMG-SWP (HG) 01/2007. Kuala Lumpur, Malaysia.

[5] Nawawi MNM, Harith ZZT, Ayub MS, Ibrahim AN, Alphonse A. Modeling of an underground water aquifer using 2-D electrical imaging technique in Brooklands Plantation. Selangor, Malaysia. 2001 In: Proceedings of the second international symposium on geophysics,

[6] Loke MH. The use of 3-D electrical imaging surveys for mapping complex subsurface structures. In: Proceedings of geological society of Malaysia seminar on the recent advances in engineering geophysics, Kuala Lumpur, 2001, pp 47– 59

To whom correspondence should be addressed - corresponding author: benawuah@ucsiuniversity.edu.my/ jbenawuah@gmail.com