Sains Malaysiana 48(5)(2019): 945–963
http://dx.doi.org/10.17576/jsm-2019-4805-03

Characterization of a Proposed Quarry Site using Multi-Electrode Electrical Resistivity Tomography

(Pencirian Tapak Cadangan Kuari Menggunakan Tomografi Keberintangan Elektrik Multi-Elektrod)

JOHN STEPHEN KAYODE, MOHD HARIRI ARIFIN* & MOHD NAWAWI

ABSTRACT

This research focuses on the delineation of subsurface basement granitic structures suitable for engineering construction materials for the sitting of quarry industry in the area. The key objective of the study was to locate and delineate the depths of burial to the subsurface granite rock bodies and the regolith thickness overlain the bedrock unit. 14 resistivity profile lines with a surveyed length of 200 m and electrode spacing of 5 m, were carried out with the application of electrical resistivity tomography software, to image the subsurface structural units around this area, utilizing pole-dipole electrode configurations method towards assisting the Engineers in obtaining information on the subsurface geological features in this part of the Peninsula Malaysia. The focus is on characterizing engineering construction materials suitable for sitting the quarry industry, determination of the longitudinal conductance and coefficient of anisotropy of subsurface lithological units that determines the competency of the bedrock underneath the area from the geoelectric parameters obtained through the interpretations of the RES2DINV ERT images. The depth of bedrock unit as delineated from the results ranged from about 5 m to 100 m while the resistivity values recorded was greater than 6000 Ω-m in most of the profiles. Groundwater bearing channels that would serve the factory needs was delineated alongside the granitic rock unit. These results make the subsurface granitic bedrock unit to be adjudged competent and suitable enough as quarry construction materials for sitting the factory in the area.

Keywords: Competency of bedrock; electrical resistivity tomography; quarry site; rocks anisotropy parameters

ABSTRAK

Penyelidikan ini memberi tumpuan kepada penentuan struktur granit bawah tanah yang sesuai untuk bahan binaan kejuruteraan bagi penempatan industri kuari di kawasan tersebut. Objektif utama kajian ini adalah untuk mencari dan menentukan kedalaman jasad batuan granit yang tertimbus dan ketebalan unit batuan dasar regolith. 14 garis profil keberintangan dengan panjang 200 m dan jarak elektrod 5 m, telah dijalankan dengan menggunakan perisian tomografi keberintangan elektrik (RES2DINV) untuk menggambarkan unit-unit struktur bawah permukaan di sekitar kawasan ini, menggunakan susunatur elektrod kutub-dwikutub dengan bantuan jurutera dalam mendapatkan maklumat mengenai ciri geologi bawah permukaan di kawasan Semenanjung Malaysia. Tumpuannya adalah untuk mencirikan kesesuaian bahan binaan kejuruteraan untuk penempatan industri kuari, penentuan konduktan membujur dan pekali anisotropi unit litologi bawah permukaan yang menentukan kebolehgunaan batuan dasar di bawah kawasan kajian daripada parameter geoelektrik yang diperoleh melalui tafsiran imej RES2DINV ERT. Kedalaman batuan dasar yang telah ditentukan daripada hasil tersebut adalah berjulat sekitar 5 m hingga 100 m dengan nilai bacaan keberintangan yang direkodkan adalah lebih besar daripada 6000 Ω-m pada kebanyakan profil. Laluan yang mengandungi air bawah tanah yang boleh membekalkan keperluan kepada kilang telah ditentukan di sepanjang unit batuan granit. Keputusan ini menjadikan unit batuan granit sesuai dan layak digunakan sebagai bahan binaan kilang di kawasan tersebut.

Kata kunci: Kecekapan batuan dasar; parameter anisotropi batuan; tapak kuari; tomografi keberintangan elektrik

INTRODUCTION

Peninsular Malaysia has witnessed lots of rapid growth in the industrial sector of the economy that caused first expansion of the people's environment through the construction of infrastructural facilities such as roads, bridges, high-rise buildings, and so on. One of the priority considerations is the availability of construction materials for these engineering structures; therefore, a preconstruction investigation of the proposed quarry site is required to ascertain the availability of the host earth raw materials for the industry. Therefore, this calls for a better understanding of the subsurface geometry and the structural setting in the area proposed for the sitting of this industry. As a result of this, an understanding of the dynamics of the peninsular is vital given the huge financially viable the industry will offer the people and the government.

Geophysical prospecting methods have found many applications in the field of engineering study, they give a two-dimensional image of the subsurface structures thereby providing significant information that is necessary for engineering site development. This study focuses on the application of electrical resistivity tomography, ERT (Abidin et al. 2017; Chambers et al. 2012; Panek et al. 2008), method to delineate subsurface basement structures suitable for the quarry construction materials. In a basement terrain, information on the thickness of the overburden strata and the location of the bedrock unit in sitting industry are crucial in the design of any civil engineering structure and the solution for other specific technical problems are addressed through the application of geophysical and or geotechnical methods (Abidin et al. 2017; Ringstad et al. 2000).

A significant number of researchers have applied ERT to determine subsurface thicknesses, lithologies and their depths in an attempts to recognize the bedrock capability, (Baines et al. 2002; Berge 2014; Chambers et al. 2012; Kneisel 2006; Soupios et al. 2007; Stan & Stan-Kłeczek 2014; Zhu et al. 2009).

In any engineering construction works, understanding of the bearing capacity through strength and warp behaviour of subsurface fractured rock, helps in the design of the superstructures to be sited on it. To this end, the subject of anisotropy in characterising these rock materials that assist in the designing of such engineering structures is vital. This is essentially because subsurface rock material is not regular in geometry and hence, non-uniform in shapes. For better and fast decision that incorporates cost effectiveness, the application of geophysical methods stand better advantage than the usual engineering laboratory tests of construction materials strengths.

The use of a non-natural supply of electric currents in active geophysical prospecting methods utilising resistivity techniques, through the introduction of the electrical currents into the subsurface strata by direct insertion of metal electrodes produced from steel materials, with the potential difference, V, arising from the flow of electric currents is recorded at an erstwhile electrodes spots. For a near infinitely conducting subsurface earth layers of continuous resistivity values, that are thought to be entirely homogeneous and isotropic in nature, enclosed with the earth materials, where the electric current is injected into the first current electrode, C_1 through the subsurface strata, (Figure 1). Given the fact that the subsurface earth medium is semi-circular in nature, the pattern of the electric current flow is radial in shape through the subsurface earth regions to the second current electrode at point C_2, (Figure 2). The flow of electric current from the first electrode C_1, to the second current electrode C_2, enable the determination of the subsurface earth's materials' resistivity, ρ, at any level. The position at which the electric current penetrated the subsurface earth's material medium is designated with positive I, while the outlet point from the earth's medium is designated by negative I. (Kearey et al. 2002).

Taken an arbitrary position, P, within an enclosed subsurface earth's materials medium from the first electrical current source electrode, at a space of say, r, assuming the enclosed subsurface earth material is in shape with surface area of $2\pi r^2$, then the potential arising from the uniform half-plane subsurface lithologic units is given by (1);

$$\Phi(r) = \frac{\rho I}{2\pi r}. \tag{1}$$

The circulation of the potential fields within the subsurface earth's materials is uniform about the vertical section sited at the centrally located and flanked by the two current electrodes. Equation 2 gives the potential established at any arbitrary position from a given duo current electrodes;

$$\Phi(r) = \frac{\rho I}{2\pi}\left(\frac{1}{r_{C1}} - \frac{1}{r_{C2}}\right), \tag{2}$$

where; r_{C1} and r_{C2} are the respective distances from the first and the current terminal electrodes to the random location (Kearey et al. 2002).

Often, it is the potential difference dropped across two connected positions with the potential electrodes that are typically recorded during the field data collection. The injecting current electrodes, C_1, could be used, in theory, to measure the potential difference, V, dropped across the two potential electrodes, (P_1 and P_2), although the overbearing impact of the resistances amongst the subsurface earth

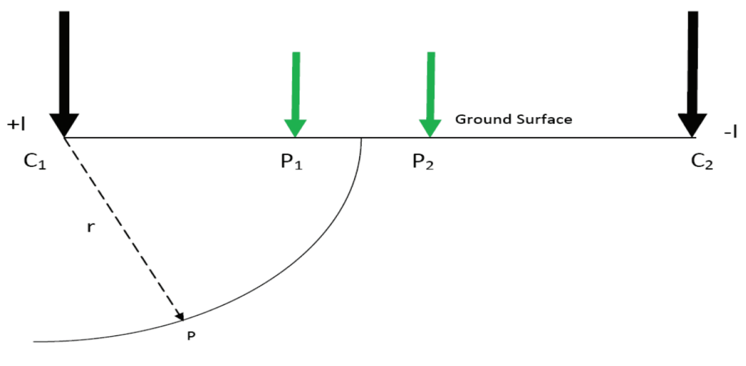

FIGURE 1. Current is flowing from the source through homogeneous earth medium producing a potential field uniformly distributed into the subsurface geological structures, modified after Kearey et al. (2002)

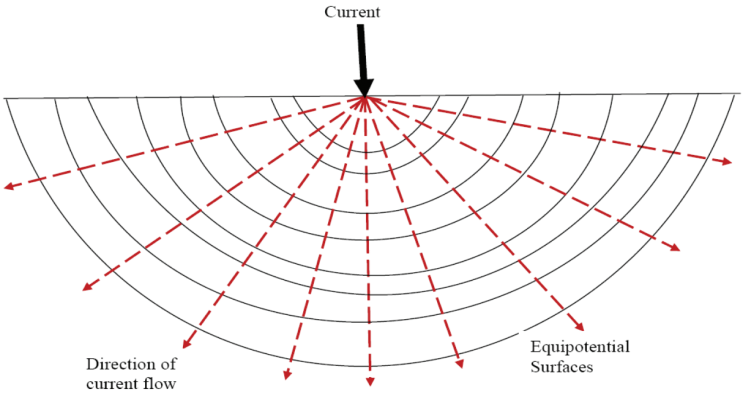

FIGURE 2. The uniformly potential field distributions within the subsurface structures when current flow from C_1 through the earth medium to C_2 modified after Kearey et al. (2002)

strata and the current electrodes is not specifically known as reported in Cheng et al. (1990). Therefore, the two potential electrodes, P_1 and P_2 shown in Figure 1 are dedicated to detecting the response signal of the potential difference dropped within these current electrodes. This value of the potential difference dropped across P_1 and P_2 are expressed by (3);

$$\Delta\Phi = \frac{I\rho}{2\pi}\left(\frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2}\right). \tag{3}$$

Equation 3 provides the potential difference measured across an identical hemispherical segment with the applications of four electrode arrays configurations. The subsurface geological structural units are naturally diverse in in-situ; hence, the quantity of the resistivity values measured at the ground surface is the definite quantity, i.e., the resistivity values for a homogeneous subsurface lithological units that will produce similar resistivity values for an identical electrode arrays, that is commonly referred to as the 'Apparent' values.

Furthermore, the apparent resistivity values are the biased mean values recorded for the subsurface earth materials beneath all the electrodes, i.e., C_1, C_2, P_1 and P_2, in four electrodes arrays. The apparent resistivity consequently depends on the configurations of the electrodes and is determined by the quantity of electric current injected to the subsurface strata and the resulting voltage ΔΦ, dropped across the electrodes. Equation 4 adequately defined apparent resistivity ρ_a of a subsurface earth geological medium;

$$\rho_a = G\frac{\Delta V}{I}. \tag{4}$$

The quantity G, is a function of the electrode configurations that is commonly called, 'the geometric factor *G*' given by (5);

$$G = 2\pi / \left(\frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2}\right). \tag{5}$$

Electrical Resistivity Tomography is also commonly referred to as Electrical Ground Imaging, EGI. ERT is an advanced geophysical method used to verify the subsurface resistivity distribution through ground surface measurements. ERT data are rapidly measured using an automated multi-electrode resistivity instruments (Figure 3).

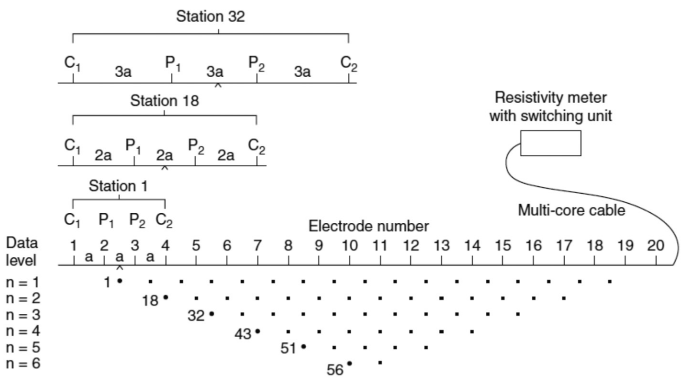

FIGURE 3. Schematic diagram of a multi-electrode system for 2D resistivity imaging modified after Kearey et al. (2002)

GEOLOGY OF THE STUDY AREA

Kulim area is situated in the south-eastern part of the state of Kedah, Malaysia. The City evolved from a small settlement in the early fifties to a thriving built-up settlement. Geologically, this area is underlain by granitic rocks that consist of three units (Figure 4), namely; the Bongsu, Mertajam and Panchor granites that were emplaced in a reasonably small period between 180-224 Ma (Azman et al. 2000; Ghani et al. 2000). All the three units consist of rocks that ranged from the same granular fine to coarse grained syeno- to monzogranite with subsidiary porphyritic types. The essential minerals in all the granites located in this area are apatite, biotite, K-feldspar, muscovite, plagioclase, quartz, tourmaline, zircon, garnet and opaque phases (Azman et al. 2000; Ghani et al. 2000; Jasin 2008).

In the north and north-western segment of the study area is located by the Mertajam granite that is subjugated by medium to coarse-grained biotite granites and slightly porphyritic micro-granites. Magnificent quality outcrops of this unit could be seeing at Bukit Mertajam, Juru, Kulim and Penanti areas as reported by the authors. About sixty-five percent of the granitic rocks in the study area formed the Bongsu granite. These authors also reported that the rock grades that varied from medium to coarse-grained biotite-muscovite granites with porphyritic varieties occurred mostly in the northern part of the Bongsu pluton and was said to be characterised by muscovite crystals that could surpass 1 cm occasionally. This lithologic unit could be seeing in areas such as; Gunung Bongsu, Terap and Sungai Karangan. The least unit of the Bukit Mertajam-Kulim granites is located mainly in the southern segment of the area with fine to coarse-grained porphyritic biotite (Azman et al. 2000; Cobbing 2000; Ghani et al. 2000; Gobbett & Hutchison 1973; Haile 1980; JMG 2014; Khoo & Tan 1983). The elevation above mean sea level recorded was between 51 and 147 m. The topography is hilly to undulating and also low with most areas covered by palm plantation as shown in Figure 5 (Chung et al. 2017; Mohamad & Roslan 2017).

MATERIALS AND METHODS

ERT survey was carried out using a multi-electrode system. The pole-dipole array was selected, (Figure 6), which could affect the inversion model. It has relatively good uniform coverage and higher signal strength compared to a dipole-dipole array. It is much less sensitive to telluric noise than the pole-pole array. The combined measurements of the forward and reverse pole-dipole array would remove any bias in the model due to asymmetry. However, this will increase the survey time as the number of data points to be measured will be doubled. The signal strength of the pole-dipole array is lower than that of Wenner and Schlumberger arrays, and is very sensitive to vertical structures (Kearey et al. 2002; Loke 2014; Mohamad & Roslan 2017; Panek et al. 2008).

Due to the significant degree of diversity of the lithological and dynamic variation and contrast between the different layers in the subsurface of the study area, ERT geophysical method was selected and used to delineate materials for the quarry factory from the subsurface structures. The ERT profiles consist of a modelled cross-sectional two-dimensional plots of resistivity values in Ω-m units against the depths of the subsurface structural units.

The 2-D ERT survey was carried out with ABEM SAS4000 Terrameter together with a selector, ABEM

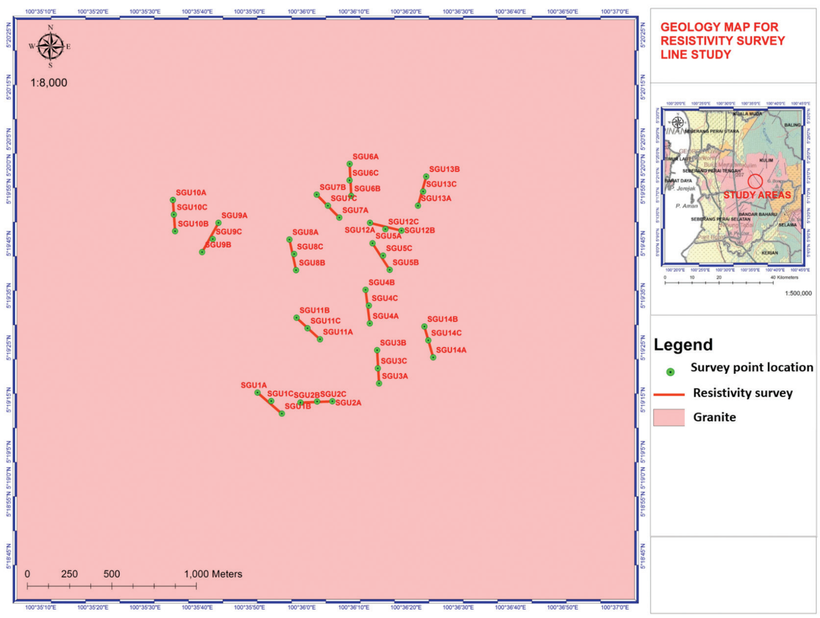

FIGURE 4. The geology map of Kulim area showing the resistivity surveyed lines

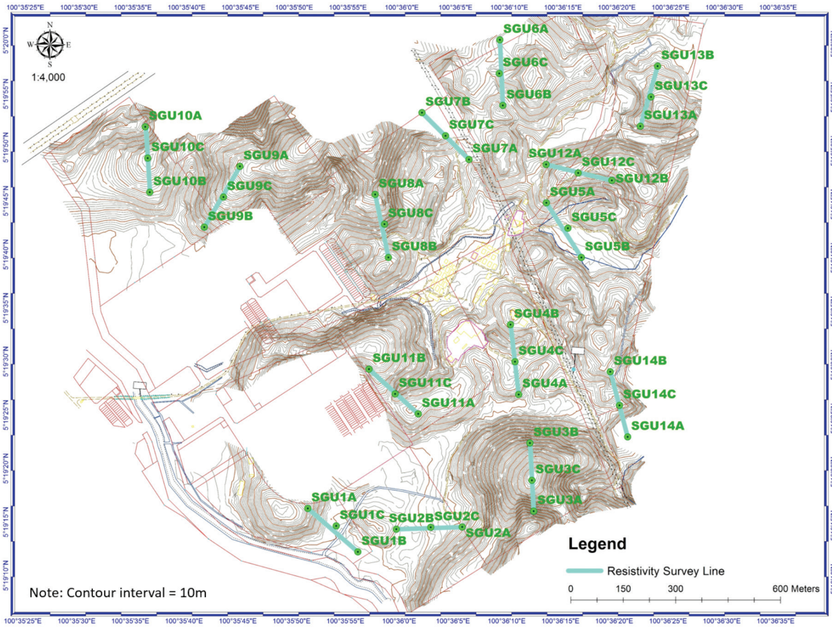

FIGURE 5. Topographical map and resistivity survey layout lines of the study area

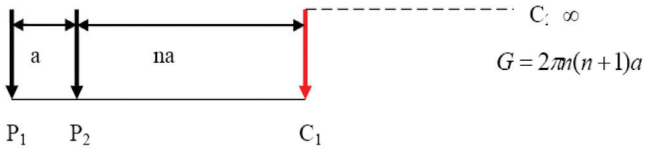

FIGURE 6. Electrode configurations used in this survey, Pole-Dipole Array modified after Telford et al. (1990) and Kearey et al. (2002)

LUND ES10-64; two reels of 100 m length each, metal electrode cables at 5 m electrode spacing with stainless steel electrodes materials. Each of the 2-D ERT surveyed profile lines comprises of a single electrode spread of 200 m utilising 41 electrodes with the application of pole-dipole electrodes array technique. The RES2DINV software was used to modelled the resistivity field data (Loke et al. 2015, 2014, 2013; Rucker et al. 2010; Wilkinson et al. 2013).

Approximation of subsurface rocks anisotropy is precious when prospecting for engineering construction materials to help in the design, planning and selection of the construction materials.

Previous research (Amadei 2012; Gonzaga et al. 2008; Hakala et al. 2007; Kearey et al. 2002; Kneisel 2006; Worotnicki 2014) stressed the importance of these parameters in dealing with subsurface engineering construction materials. Meanwhile, the degree of inhomogeneity of subsurface rocks determined the properties of the electrical anisotropy in a basement environment that was said to be promoted through rock joints, the degree of faulting/fracturing and weathering profiles traversing a joint planes in a region (Mallik et al. 1983). In this paper, we explore the effect of this subsurface rock anisotropy on the granitic basement rock units of Kulim area about its suitability for use as Quarry construction materials through the application of ERT method.

The advantages of studying subsurface granitic rock engineering properties around Kulim area in Peninsular Malaysia lies on the subsurface excavations stability during the construction works; it is very relevant to the processes of rock blasting and drilling operations. Knowledge of rocks anisotropy of this area could also help in stabilising engineering foundations and ground surface excavation activities during operations at the site. On the final note, subsurface fluids flow and contaminations hauling could be better appreciated through rocks anisotropy parameters for further engineering characterization of the area. Equations 6 - 10 present the rocks anisotropy parameters as extracted from the subsurface geoelectric parameters of thicknesses and resistivity values that helped to characterise better, the Kulim subsurface geological rocks.

The longitudinal conductance, S, in mhos, as shown in (6), i.e., the measure of the overall thickness, h, of the low resistivity subsurface strata overlain the bedrock unit (known as the regolith), divided by the resistivity value, ρ, of the bedrock unit. Alternatively, it is the absolute depths to the bedrock subsurface unit, divided by the resistivity value, ρ, of the bedrock unit. Meanwhile, Balasubramanian et al. (1985), ascribed low values of longitudinal conductance to shallow bedrock unit in complex geological environments, and high values of S, to that of a deep seated bedrock unit in a complex geological basement environments such as we have in this study area.

$$S = \frac{h}{\rho}. \tag{6}$$

The products of these regolith thicknesses, h, above the bedrock, and that of the bedrock resistivity, ρ, defines the traverse unit resistance, T_r, in Ω-m^2, shown in (7). This quantity, T, was defined to be a hydraulic property of subsurface materials (Amadei 2012; Hakala et al. 2007). Therefore, T, as a function of either thickness, h, and resistivity, ρ, of subsurface geological layers, could give very high values when any of these two parameters is high. For a basement geological rock unit to be adjudged competent for engineering purposes, this quantity must be at very high values (Worotnicki 2014).

$$T_r = h\rho. \tag{7}$$

Equation 8 presents the longitudinal resistivity, ρ_l, that was defined by dividing the values of the thicknesses, h, above the bedrock unit by the values obtained from the computations of the longitudinal conductance, S.

$$\rho_l = \frac{h}{S}. \tag{8}$$

The traverse resistivity, ρ_t, was computed from the products of the reciprocal values of the thicknesses, h, above the bedrock subsurface unit, and the transverse unit resistance, T_r, presented in (9).

$$\rho_t = \frac{T}{h}. \tag{9}$$

Numerous works have defined the anisotropy of complex basement subsurface geological rock units in relation to their engineering applications (Chandra et al. 2008; Gonzaga et al. 2008; Hakala et al. 2007; Kneisel 2006; Mallik et al. 1983; Nunes 2002; Panissod et al. 1998; Rao et al. 2003; Soupios et al. 2007; Sudha et al. 2009; Van Heerden 1983). It is commonly referred to as the 'Coefficient of Anisotropy' in some of the literature. This quantity, as expressed in (10), and defined by the geoelectrical parameter mostly occurred in basement terrain because of the effects from adjacent surface-subsurface strata on the bedrock units.

$$\lambda = \sqrt{\frac{\rho_t}{\rho_l}}. \tag{10}$$

These near-surface effects, such as, subsurface geological features like faults /fractured bedrock, joints and weathered bedrocks are accountable for the permeability and porosity that are paramount in the selection of any engineering construction materials within the subsurface complex geological rock units.

Results and Discussion

The most compelling objective of this study is to acquire sufficient subsurface geological information from the ERT field data to permit the reliable determination of the granite-gneiss rock units, its depths of burial in addition to the lateral coverage of the subsurface structures. The depth, thickness and the extent of all the main top soils and rock strata that will be useful for the quarry construction work to be sited in the area, would be determined in reasonable detail. Electrical Resistivity Tomography geophysical method has repeatedly fulfilled these desires for obtaining rapid and cost-effective subsurface information and is thus indispensable tools in preliminary surveys for engineering sitting purposes, as it provides relevant information for bedrock prospecting and yield unambiguous resolution of the general subsurface structures (Soupios et al. 2007). The results from each ERT profile are discussed separately to provide detail interpretations of each of the profiles. The RES2D surveyed line for ERT along profile 1 (Figure 7), was conducted in the Northwest-Southeast directions that

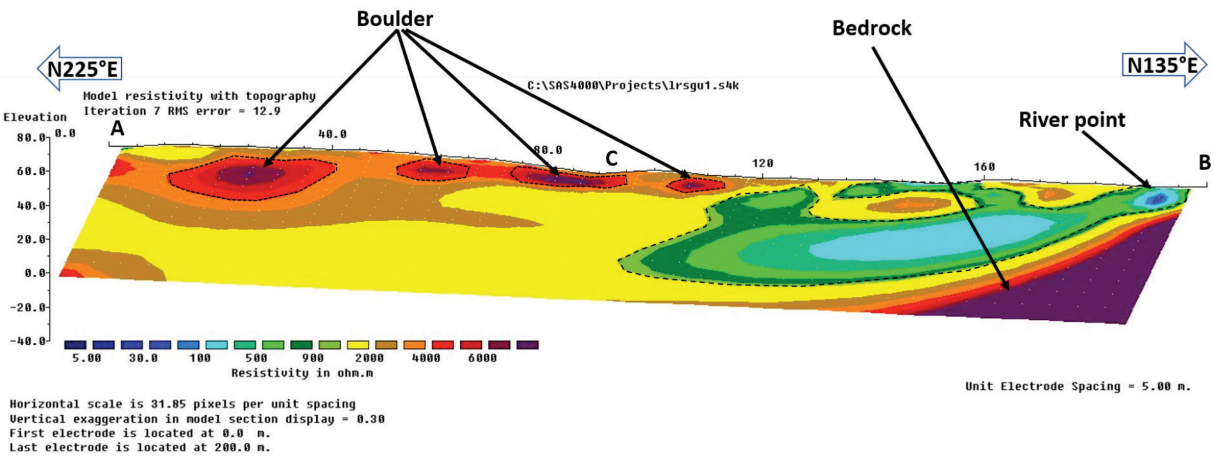

FIGURE 7. Inverted RES2D ERT along Profile 1 of the study area

covered a survey distance of 200 m at an electrode spacing of 5 m. The inversion ERT image showed the bedrock depths located at about 60 m along the horizontal distance of about 175 m from the first electrode position at point A. The resistivity value obtained at this stage is greater than 6000 Ω-m. The overburden thickness was estimated to be greater than 75 m between the first electrode at point 0 m, and the centre electrode at 100 m with a thickness of about 10 m at the last electrode position of 200 m from the first electrode, (point B). The resistivity values of the overburden materials along this profile ranged from between about 5 Ω-m to less than 2000 Ω-m.

The result of RES2D Inversion along the surveyed line of profile 2 is as presented in Figure 8. It runs approximately along East-West directions with a total distance of 200 m at an electrode spacing of 5 m. The RES2D yields different subsurface structures that exclude the granitic bedrock unit. Some pockets of boulders were delineated near the ground surface at a depth of about 5 m. This profile constitutes very thick overburden materials and a groundwater bearing structural channels. The result showed very low resistivity values of the regolith that ranged from about 5 Ω-m to greater than 1000 Ω-m. The absence of granitic bedrock unit, or probably at a greater depth than the surveyed spread could delineate this site unsuitable for the sitting of the Quarry factory. Alternately, the zone has a greater potential for groundwater prospecting to serve the factory needs.

Profile 3 surveyed line was approximate along North-South directions with a total distance of 200 m at an electrode spacing of 5 m (Figure 9). RES2D Inversion generated for this profile showed the depths to the granitic bedrock unit at about 90 m from the ground surface and a surface distance of about 170 m from the first electrode position. The highest resistivity value recorded along this profile was greater than 2000 Ω-m. The maximum elevation of about 147 m has been registered along the profile with very thick overburden strata that include some boulders and compacted sand that are very near to the surface. The RES2D showed a deeply weathered granite gneiss as noticed by the presence of residual soil materials that was yellowish /orange in colour. At a surface distance of 45 m from the first electrode position, and at depths of about 50 m was delineated a groundwater channel, with the lowest resistivity values less than 100 Ω-m. The minimum overburden thickness in this area was estimated to be about 70 m.

The Inverted RES2D resistivity surveyed for profile 4 was conducted along the North-South directions with a total surveyed spread of 200 m. From the RES2D showed

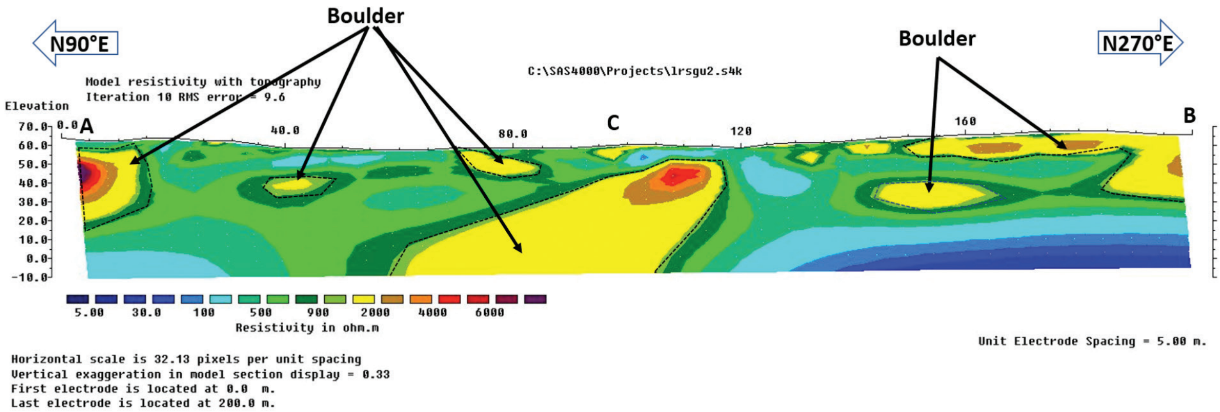

FIGURE 8. Inverted RES2D ERT along Profile 2 of the study area

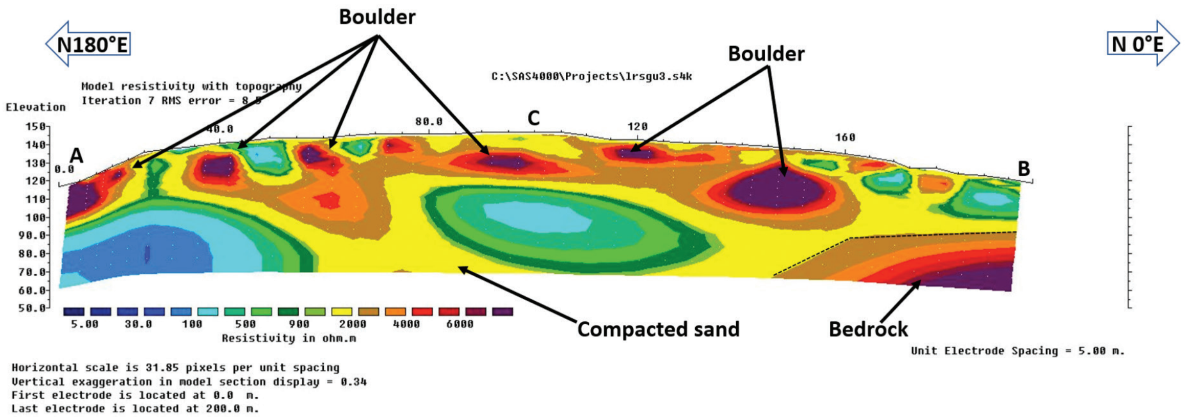

FIGURE 9. Inverted RES2D ERT along Profile 3 of the study area

in Figure 10, the overburden thickness was estimated to be greater than 65 m with resistivity values that varied from between about 100 Ω-m and about 1000 Ω-m. The major anomaly delineated along this profile is groundwater with an average range of the resistivity values less than about 100 Ω-m at a depth of less than about 40 m. Although, this profile may be unsuitable for the sitting of the Quarry engineering materials, the zone has a greater potential for groundwater prospecting to serve the factory needs.

Profile 5 was carried out approximately along Northwest-Southeast directions and covering a total horizontal surveyed spread of 200 m (Figure 11). The RES2D produced from the RES2D inversion ERT model showed the granitic bedrock unit with resistivity values greater than 2000 Ω-m at a depth of about 60 m. The overburden thickness was estimated to be about 60 m with resistivity values of the overburden strata in the range from between about 5 Ω-m and 2000 Ω-m.

The Electrical Resistivity Tomography RES2D along profile 6 was presented in Figure 12. The surveyed line runs approximately in the North-South directions with a total surveyed length of 200 m. The interpreted results as presented from the ERT delineated the bedrock unit at about 50 m depths along a horizontal distance from point A, the initial position of the first electrode, 0 m, up to about 110 m amid resistivity value greater than about 2000 Ω-m. The thickness of the overburden materials along the profile was approximated to be greater than 70 m between about 110 m to 190 m along the surveyed line. The resistivity values of the overburden strata obtained ranged from between 0 Ω-m up to about 6000 Ω-m.

Figure 13 presents the RES2D ERT along the surveyed line of profile 7. The traverse runs approximately in the Northwest-Southeast directions. The granitic bedrock unit was delineated at depths of about 10 m from the ground surface at some few metres away from the initial and last electrode positions of points A and B, respectively, amid resistivity values that exceeded 6000 Ω-m. Besides that, two positions of high resistivity values were delineated between about 100-140 m along the surveyed line with values in the order of about 2000 Ω-m at an approximate depth of about 70 m. Overburden materials along this traverse have resistivity values between 0 Ω-m and about 2000 Ω-m at a maximum depth of 80 m between the horizontal distance of about 70-100 m along the profile spread. Besides this, the regolith depths were delineated at about 15 m between the respective horizontal distances of about 0 m-70 m and 140 m-200 m.

Resistivity surveyed line along profile 8 was conducted approximately in the North-South directions covering a

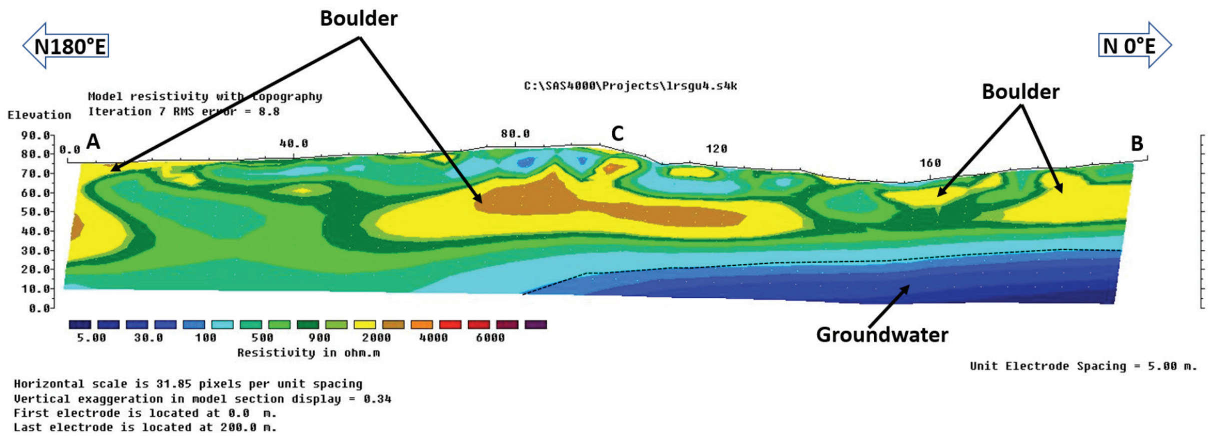

FIGURE 10. Inverted RES2D ERT along Profile 4 of the study area

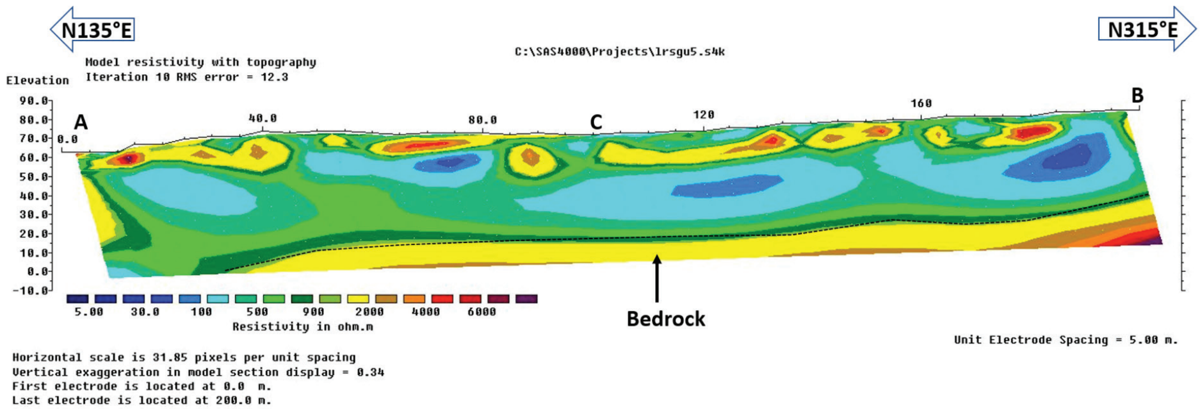

FIGURE 11. Inverted RES2D ERT along Profile 5 of the study area

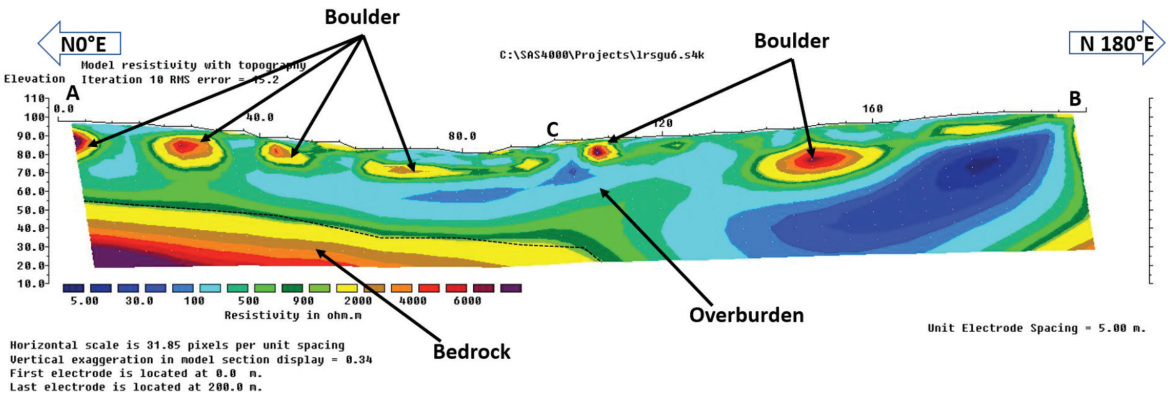

FIGURE 12. Inverted RES2D ERT along Profile 6 of the study area

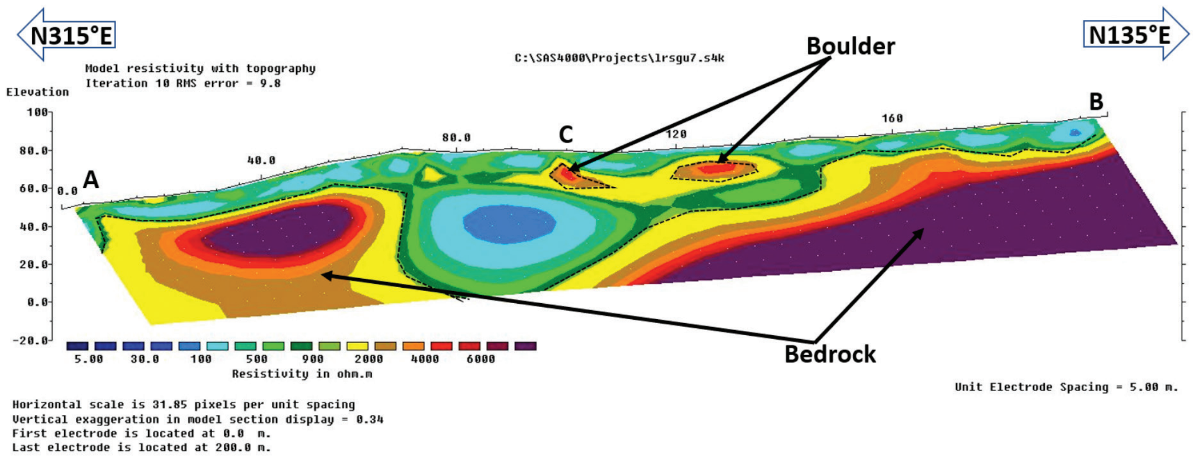

FIGURE 13. Inverted RES2D ERT along Profile 7 of the study area

total horizontal spread of 200 m. The RES2D inversion was presented in Figure 14. Depths to the bedrock subsurface unit were delineated at about 50 m beneath the electrode initial position at point A amid resistivity values much greater than 6000 Ω-m. The thickness of the overburden materials along this surveyed line was delineated to be greater than 10 m beneath the electrode initial position spreading up to about 40 m. Besides this, overburden strata were delineated at depths of about 70 m beneath horizontal distance of between about 85-150 m amid resistivity values that ranged from between about 5 Ω-m and 2000 Ω-m. Though, boulders of granitic rock units were delineated at distances of about 20 m, 60 m and between 130-180 m along the surveyed line, the presence of groundwater bearing channels was delineated underneath the horizontal distances from between about 70 m through to about 145 m.

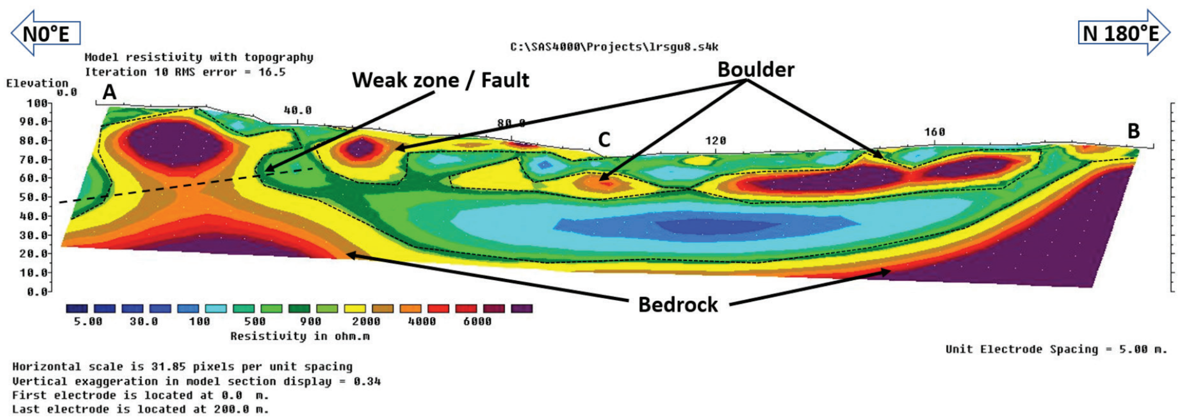

FIGURE 14. Inverted RES2D ERT along Profile 8 of the study area

The results of the surveyed line accomplished along profile 9 were presented in Figure 15. The profile runs approximately in the Northeast-Southwest directions covering a total horizontal spread of about 200 m utilising electrode spacing of 5 m. Four subsurface lithologic units were delineated as presented by the RES2D inversion ERT with groundwater bearing channels emplaced massively beneath the surveyed line. Besides this, massive granitic boulders were delineated above the groundwater body that was closely followed by a fractured/faulted bedrock like structure, trending approximately along Northeast-Southwest directions amid shallow point at the centre electrode position and steeply dipping towards the North-Eastern directions. The granitic bedrock unit was delineated at a horizontal distance from between about 185 m and 200 m and almost expose to the surface at about 190 m. The resistivity values obtained from the RES2D inversion for the subsurface lithological units delineated along this profile ranged from about 5 Ω-m to about 1000 Ω-m for the overburden materials, and greater than 6000 Ω-m in the case of the boulders and the granitic bedrock unit. The fault/fracture structural units have resistivity values delineated in the range of between about 1000 Ω-m and 2000 Ω-m. Depths to the subsurface strata were delineated at about 20 m except the 5 m depths delineated underneath the horizontal distance of about 190 m where the subsurface granitic rock unit is very close to the ground surface.

Profile 10 was selected along approximate North-South directions as presented in Figure 16. Subsurface groundwater bearing channels was delineated at depths of about 45 m spreading from the electrode initial position along a horizontal distance of the surveyed line up to about 140 m. This lithological unit present low resistivity values in the order of about 100 Ω-m most probably to be groundwater bearing channels. Compacted sands with resistivity values of between about 1000 Ω-m and 2000 Ω-m were delineated in two places along the profile line at about 30 m and 100 m from the first electrode position respectively. On top of the low resistivity lithological units, there is the presence of boulders with very high resistivity values greater than 4000 Ω-m in three places along the profile spread at about 45 m, 65 m and 150 m, respectively. The granitic bedrock unit with resistivity values greater than 6000 Ω-m was delineated between about 170 m and 200 m along the horizontal profile line. The minimum thickness of the overburden in this area is about 95 m.

Electrical resistivity tomography surveyed along profile 11 (Figure 17), was carried out approximately in

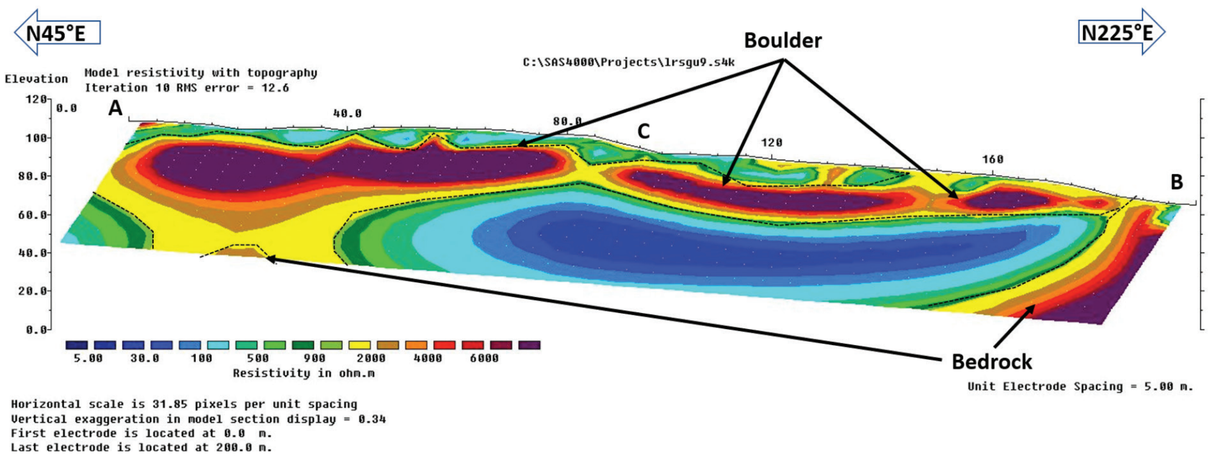

FIGURE 15. Inverted RES2D ERT along Profile 9 of the study area

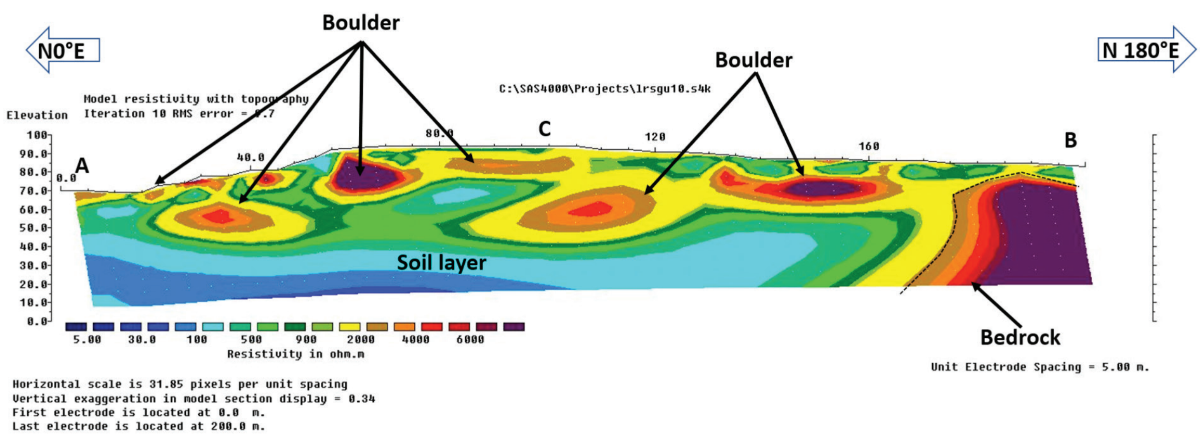

FIGURE 16. Inverted RES2D ERT along Profile 10 of the study area

the Southeast-Northwest directions covering a maximum spread of 200 m. The RES2D inversion showed the bedrock unit sited at the right bottom corner at a distance of about 170 m from the first electrodeposition of point A, distributed to the last electrodeposition at point B, (200 m) where the depths to the bedrock became very shallow with resistivity values greater than 6000 Ω-m and depths that varied from about 5 m and 100 m. The overburden thick was estimated to be greater than 80 m between the electrode initial position at point A, (0 m) extending to about 170 m along the profile line with resistivity values delineated in the range from 10 Ω-m and 1000 Ω-m.

Profile 12 was conducted along approximately Northwest-Southeast directions with a maximum surveyed distance of about 200 m. The RES2D inverted electrical resistivity tomography showed in Figure 18, two boulders located at about 5 m depths from the ground surface and extended to the last electrode position at point B, 200 m. The granitic bedrock unit could be possibly emplaced beyond the surveyed distance covered. The resistivity values recorded for the boulders was greater than 6000 Ω-m. Overburden thickness delineated along this profile line varied between about 50 m around the central part and greater than 100 m at about 20 m from the electrode initial position distributed to the centre electrode position. The resistivity values recorded for the overburden soil materials varied between about 5 Ω-m and 2000 Ω-m at a horizontal distance of about 25 m to about 50 m. Groundwater accumulation channel was delineated at about 80 m distributed through to about 175 m.

Figure 19 shows the resistivity surveyed spread along profile 13. It was conducted along approximately South-North directions with a maximum surveyed horizontal spread of about 200 m. The 2-D resistivity tomography showed granitic bedrock unit sited at depths of about 30 m along the horizontal distance of about 155 m from point A at 0 m, and at depths of about 5 m at point B, 200 m, with recorded resistivity values greater than 6000 Ω-m. The overburden thickness along this profile was estimated to be greater than 120 m at the central segment with very low resistivity values that ranged from between about 0 Ω-m and about 2000 Ω-m. A boulder of conical shape structure with resistivity values greater than 2000 Ω-m was located between the electrode initial position distributed up to about 80 m. A subsurface valley like structure was delineated at the central portion of the surveyed line along this profile. This structure could probably be a faulted plain filled with low resistivity strata such as clayey materials.

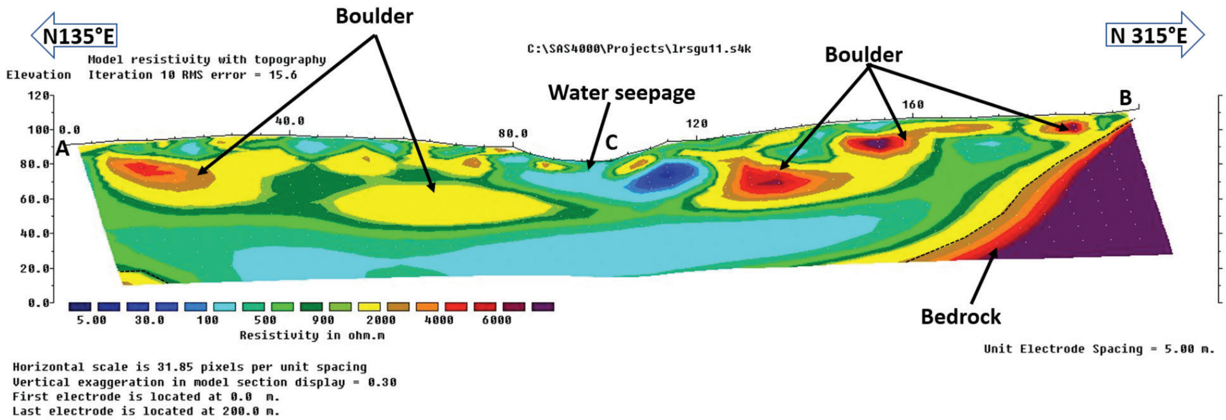

FIGURE 17. Inverted RES2D ERT along Profile 11 of the study area

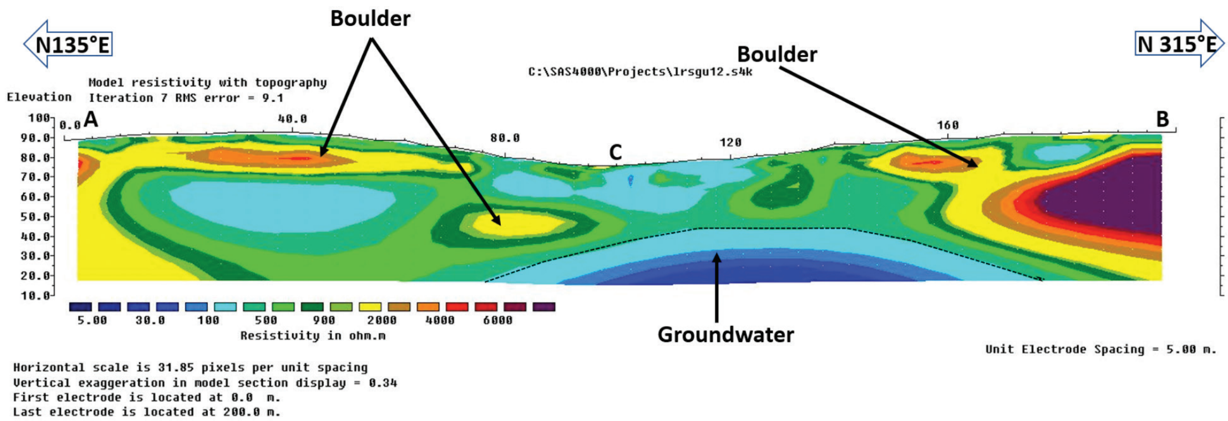

FIGURE 18. Inverted RES2D ERT along Profile 12 of the study area

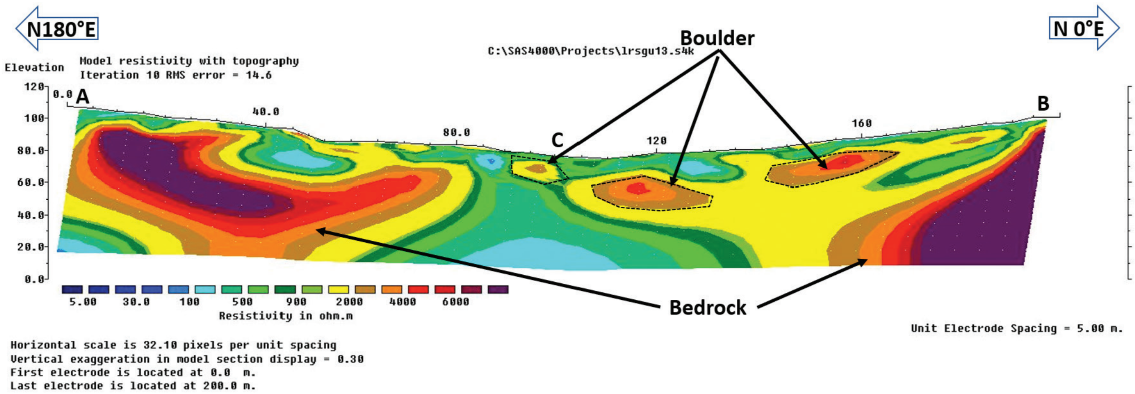

FIGURE 19. Inverted RES2D ERT along Profile 13 of the study area

The RES2D inversion electrical resistivity tomography along profile 14 was conducted approximately in the South-North directions with a surveyed spread of 200 m (Figure 20). The interpreted pseudo-sections showed the bedrock unit sited at minimum depths of about 5 m from the ground surface, some few metres away from the last electrode position at point B (200 m), with recorded resistivity values greater than 6000 Ω-m. The overburden strata along the surveyed line presented a moderately high resistivity values that ranged between about 0 Ω-m and 2000 Ω-m, and a minimum thickness of about 30 m at about 50 m from the first electrode position of point A, spreading through to the last electrode position at point B. However, from point A to about 40 m, the thickness of the overburden soil materials was delineated at about 75 m with low resistivity of between about 100 Ω-m and moderately high at about 1000 Ω-m. Groundwater bearing channels were delineated between about 120 m and about 180 m beneath the granitic boulders that characterised the upper part of the overburden materials. The surveyed spread could be extended beyond the 200 m at point be to map better the granitic bedrock unit at this point.

GRANITIC BEDROCK PARAMETERS OBTAINED FROM ELECTRICAL RESISTIVITY TOMOGRAPHY

Table 1 summarises the results of the bedrock parameters as interpreted from the RES2D ERT pseudo-sections that generated the anisotropy coefficient parameters presented in Table 2. Most of the surveyed profile lines delineated the granitic basement rock unit at a very shallow depth except profiles 2 and 4, where the strata covering the bedrock along these profiles are excessively thick for the ERT method adopted for the research to be penetrated. It could be that the electrodes spread needs to be extended for deeper probing. On the other hand, profile 1 gave the highest overburden thickness of about 100 m at the centre electrode position that was closely followed by greater than 80 m recorded at point A of profile 11 and about 80 m along profile 7. The other profiles recorded moderately large overburden thickness, i.e., profiles 3, 5, 6, 8 and 14.

The rationale of this work is to delineate subsurface materials for Quarry Industry proposed to be sited in the area. For this purpose, it is imperative to understand the subsurface granitic basement rock units regarding its coefficient of anisotropy, λ, as relevant engineering parameters that defined porosity and permeability of the subsurface rock units. These parameters were computed from the ERT results for each profile line and presented in Table 2 below.

Figure 21 present the polar plots of; (a) the depths (m) to the granitic bedrock, (b) the Longitudinal unit conductance, S, (mhos), (c) the Transverse unit resistance, T, (Ω-m^2), and the Coefficient of anisotropy, λ. The depths

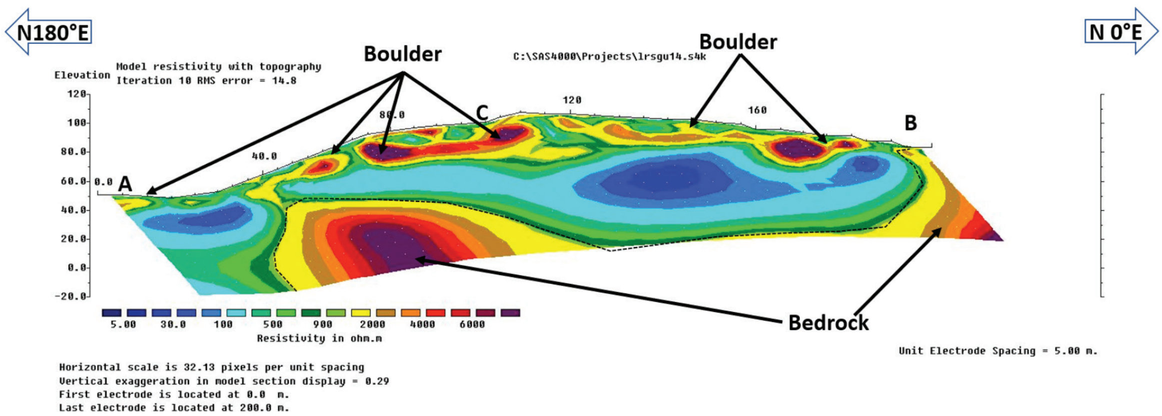

FIGURE 20. Inverted RES2D ERT along Profile 14 of the study area

TABLE 1. Bedrock parameters from electrical resistivity tomography

Profile	Depth (m)	Resistivity value (Ω-m)	Horizontal distance (m)	Overburden thickness (m)
1 (NW-SE)	100.00	>6000	175	>75 at point A, 10 at point B 100 at point C
2 (E-W)	>70.00	-	-	>70
3 (S-N)	90.00	>6000	170	70 at point C
4 (S-N)	65.00	-	-	65
5 (NW-SE)	60.00	>4000	200	>60 at point B
6 (N-S)	50.00	>6000	0-110	>70
7 (NW-SE)	10.00	>6000	90-200	80
8 (N-S)	50.00	>6000	0-200	>10 At point A, 70 At point C
9 (NW-SE)	5.00	>6000	185-200	5 At point B
10 ((N-S)	5.00	>6000	180-200	5 At point B
11 (SE-NW)	80.00 at A 5.00 at B	>6000	190-200	5 At point B >80 At point A
12 (NW-SE)	5.00 at B	>6000	200	<10
13 (S-N)	30.00 at A 5.00 at B	>6000	155-200	5
14 (S-N)	30.00 at 50m from point A 5.00 at B	>6000	50 from point A 200	>75

TABLE 2. Coefficient of anisotropy parameters from electrical resistivity tomography

Profile	Depth (m)	Longitudinal conductance, S (mhos)	Transverse unit resistance T_r (Ω-m^2)	Longitudinal resistivity ρ_L(Ω-m)	Transverse resistivity, ρ_t(Ω-m)	Coefficient of anisotropy, λ
1 (NW-SE)	100.00	0.017	600000.00	5882.35	6000.00	1.01
2 (E-W)	70.00	0.070	70000.00	1000.00	1000.00	1.00
3 (S-N)	90.00	0.015	540000.00	6000.00	6000.00	1.00
4 (S-N)	65.00	0.065	65000.00	1000.00	1000.00	1.00
5 (NW-SE)	60.00	0.015	240000.00	4000.00	4000.00	1.00
6 (N-S)	50.00	0.008	300000.00	6250.00	6000.00	0.98
7 (NW-SE)	10.00	0.002	60000.00	5000.00	6000.00	1.10
8 (N-S)	50.00	0.008	300000.00	6250.00	6000.00	0.98
9 (NW-SE)	5.00	0.0008	30000.00	6250.00	6000.00	0.98
10 (N-S)	5.00	0.0008	30000.00	6250.00	6000.00	0.98
11 (SE-NW)	80.00	0.013	480000.00	6153.85	6000.00	0.99
12 (NW-SE)	5.00	0.0008	30000.00	6250.00	6000.00	0.98
13 (S-N)	5.00	0.0008	30000.00	6250.00	6000.00	0.98
14 (S-N)	75.00	0.0125	450000.00	6000.00	6000.00	1.00

of granitic basement rock units varied between about 5 m and 100 m. Meanwhile, the longitudinal unit conductance, S, along profiles 2 and 4 approximately presented the highest values of 0.07 mhos. The depths of probing along these profile lines were unable to reach the granitic bedrock units; this could be due to the electrode spread of 200 m used for the research work. Minimum values of 0.0008 mhos were recorded along profiles, 9, 10, 12 and 13. Consequent upon this, the Transverse unit resistance recorded a maximum value of 600000 Ω-m^2 along profile 1, with profiles, 9, 10, 12 and 13 presenting a minimum value of 30000 Ω-m^2. The shallow depths of the hard-granitic rock in the area is responsible for these high values of transverse unit resistance. The coefficient of anisotropy values varied from 0.98 recorded along profiles; 6, 8, 9, 10, 12, and 13, at the same time as a maximum value of 1.1 has been registered along profile 7.

Figure 22 is the plot of coefficient of anisotropy with depths to the granitic basement rock unit. Values recorded from the anisotropy plot is an indicative of a very shallow basement that is characterised by weathered regolith. The range of values obtained suggests a deeply

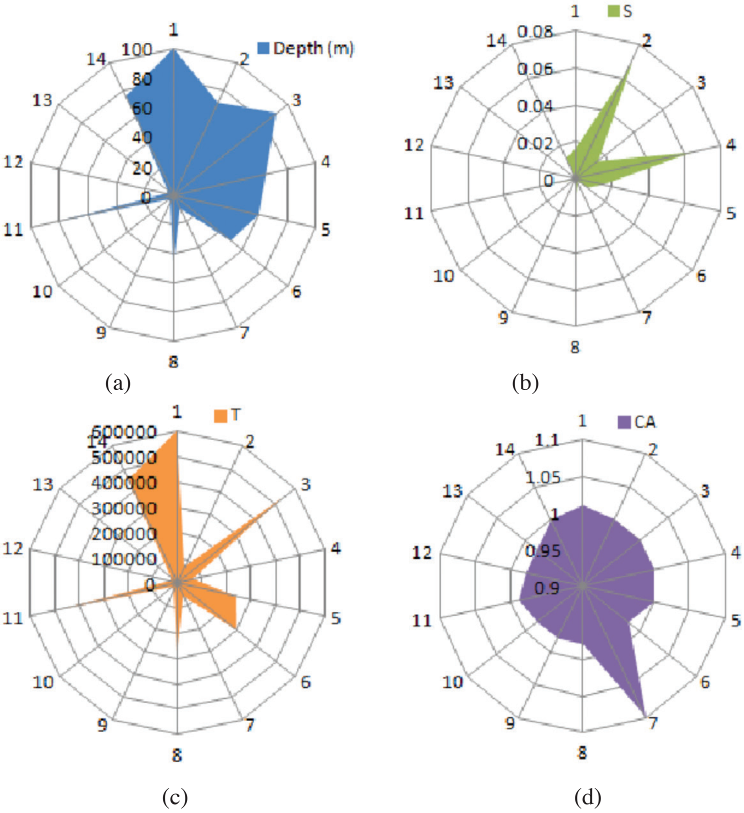

FIGURE 21. Polar diagram for; (a) Depths to the Granitic Bedrock, (b) Longitudinal Unit Conductance, (c) Transverse Unit Resistance, and (d) The Coefficient of Anisotropy of the study area

faulted and fractured subsurface bedrock that could be very useful when prospecting for groundwater. Because the spotlight of this research work is on locating and characterizing the structural features for Quarry Industry engineering materials, the results presented does not include groundwater assessment for the area. The bedrock topography is undulating and very sharp slope between profile 1 and 6 as shown. Nevertheless, between profiles 6 and 13, except profile 12, the topography is excellent coupled with fragile regolith units. The results presented supported the subsurface nature underneath profile 12, which could be inferred fault/fracture bedrock. Overall, the study area is characterised by thin regolith except profiles 2 and 4, where the granitic bedrock unit was not reached that was also supported by the longitudinal unit conductance polar plots.

The iso-resistivity map of the regolith in the study area as presented in Figure 23, was prepared to connect places with an equal resistivity of the overburden strata. The top soil covers in the area present a very low resistivity values except the south-western and southern parts of the area. The overburden lithological units were observed to be filled with very low resistivity strata from the weathered granitic bedrock unit. The sediments overlaid the basement could

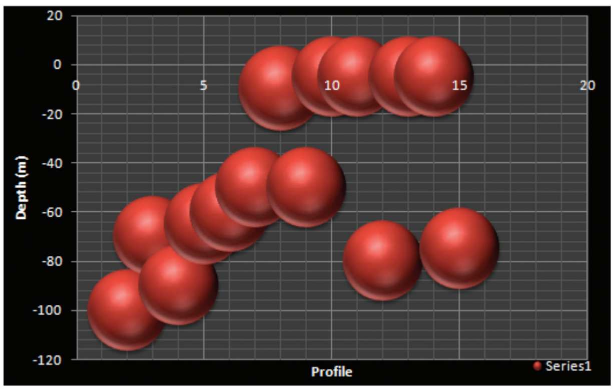

FIGURE 22. Plot of the Coefficient of Anisotropy with depths in the surveyed area

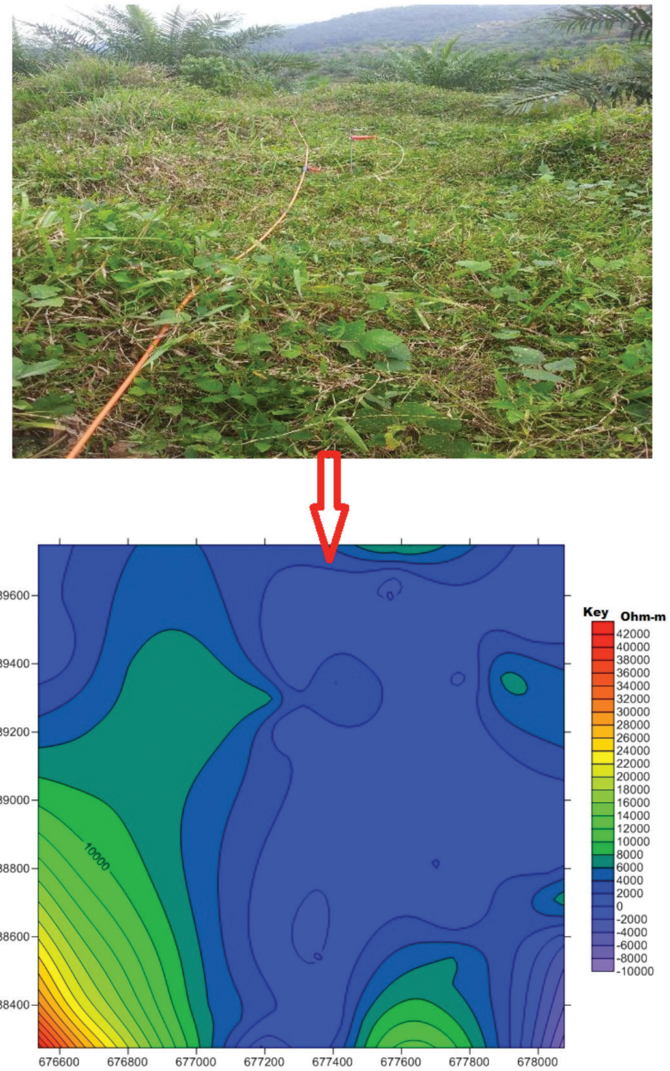

FIGURE 23. Iso-Resistivity Map of the regolith materials overlain the granitic basement rock unit of the study area

be inferred as being saturated with high moisture contents that could be groundwater bearing structures.

The iso-resistivity map of the bedrock subsurface unit as presented in Figure 24, further support the previous results shown on the suitability of the granitic materials for Quarry Industry. The thin topsoil strata delineated is an advantage of cost saving from excavation as it favours fast and less stressful in accessing the principal raw materials for the industry. The high resistivity values recorded in the area reflected the nature and structural pattern of the bedrock as observed from the ground surface. Areas with extremely low resistivity values were delineated as places covered with very thick weathered materials. This map reflects the subsurface basement structural features that coincide with places shown as ridge like geological structures at the surface. The rivers pattern of flow in this area depict the subsurface structural pattern emplacement. The elevation map of the study area was generated from the values obtained from the 2-D inversion electrical resistivity tomography results and prepared to understand better the topography. The map is shown in Figure 24, correlates well with the geological and topographical maps of the area, which also depicts the pattern and direction of flow of the drainage channels that drained the area. The two extremes north-western and south-eastern parts recorded extremely low elevation values. This map further confirmed the near plateau structural pattern observed at the ground surface around the north of the study area together with the shape of the rock along the southern central part.

CONCLUSION

The RES2D electrical resistivity tomography geophysical prospecting method denotes a suitable geophysical device in the search for several features of subsurface engineering construction materials. Nevertheless, the distinction of these subsurface geological structures requires being accorded some essential considerations. It is therefore very

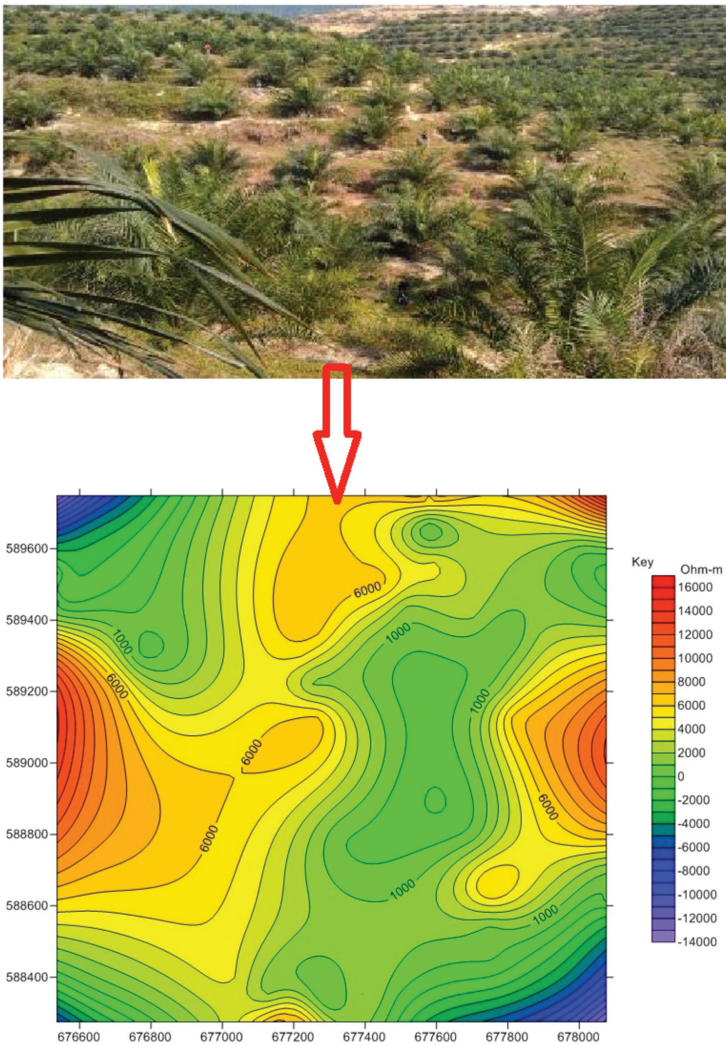

FIGURE 24. Iso-Resistivity Map of the granitic basement rock unit of the study area

essential to also ascribed selection of appropriate electrode configurations that determined the depths of investigations when applying electrical resistivity tomography method to prospect the subsurface structures in a very complex basement terrain. To effectively and efficiently monitor subsurface interior rudiments and progressive slope deformity, ERT geophysical method is essentially valuable and conveniently very helpful. The best approach in the application of ERT is in its combination of other relevant methods for confirmation purposes such as the geological and tectonic history of the study area that was done in this research work. Though the geomorphological history of a place of interest could also be used side by side with ERT to be able to have a confirmatory evidence. This research findings' results have once again proved the capability of ERT method to delineate various essential subsurface structural features emplaced in the study area that comprises the first layer embedded with high resistive granitic boulders, weathered subsurface strata with moderately low resistivity values, a groundwater bearing channel and high resistive fractured granitic bedrock unit. The lithological units showed by the method agree with the geological history of the area.

Though the ERT method is not a perfect method without some limitations, the non-invasive facts provided by the images obtained from the results are subject to misrepresentation arising from the distinction in the resistivity values of adjacent zones to the surveyed profile lines. In most cases, some additional exploration like the borehole and laboratory analysis of some rocks and soil samples are often necessary to confirm the ERT results. This could be needed for some instance as imagery results from ERT present smoothed interface locations between subsurface strata which could sometimes complicate identifications of different lithologies. In a final note, it was observed that resistivity imagery results usually experienced diminishing resolutions as the depths of probing increases. In areas where adequate information about the subsurface geology is available, borehole data that is far more expensive than ERT may not be too useful as drilling for complex basement environment such as we have in Kulim area could be tough. Considering a vast survey area as we have in this study, the use of ERT as a reconnaissance tool to achieve the desired objectives through rapid characterization of the subsurface geological structures of

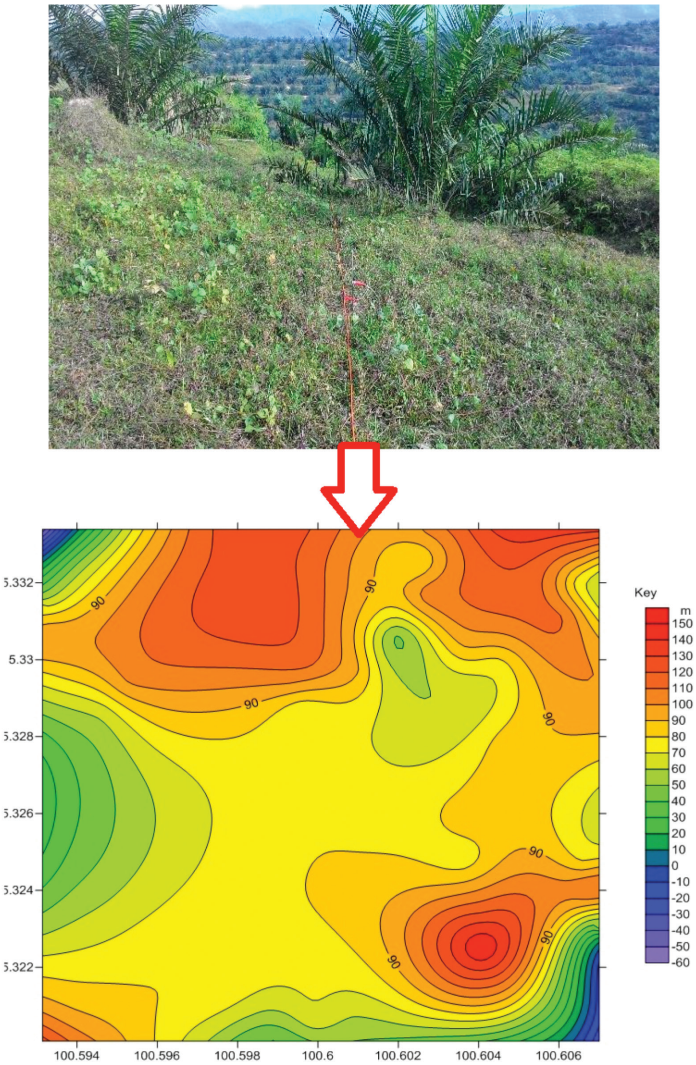

FIGURE 25. Elevation Map of the study area

the site with the choice of array spread is the best option. The RES2D inversion is considerably flexible which makes it easier to translate directly into relevant information for the effective applications by the Engineers. The method is very pertinent in the provision of complete high-quality subsurface geological bedrock surfaces assessments.

A satisfactory evaluation of the subsurface rock anisotropy parameters from the geoelectric parameters is essential in considering the suitability of the granitic rock units for the Quarry material. The geophysical technique applied for this study also helped to identify potential zones for groundwater exploration to serve the factory needs through identification of groundwater bearing structures particularly along profiles 2, 4, 6, 9, 10 and 12 that gave sufficient thickness of the aquifers beneath the overburden materials.

The RES2DINV results demonstrate an idea of the subsurface behavior of Kulim basement geological complex. However, the consequent of bulk modulus, shear modulus, and stress on the granitic rock units in this area should be considered for further research as these engineering parameters could be key factors during the construction process. Modelling of the aquifer yield and research should also be included in the future studies to better characterised the subsurface of Kulim basement complex. Our approach was intended as a geophysical tool only to advanced knowledge of the subsurface granitic rock materials considered to be suitable for sitting Quarry Industry, due to the extreme growing demand for this valuable raw material for road and building construction works. Complex subsurface ground structural behavior due to sudden changes alongside axis of basement rocks is beyond the scope of the geophysical method applied. We hope our approach would aid decisions on the use of the subsurface engineering materials for the purpose intended for this site.

ACKNOWLEDGEMENTS

The authors wish to recognise the strong efforts of the people who assisted during the fieldwork. This research was supported using grant GGPM-2018-060.

REFERENCES

Abidin, M.H.Z., Saad, R., Wijeyesekera, D.C., Ahmad, F., Baharuddin, M.F.T., Tajudin, S.A.A. & Madun, A. 2017. The influences of basic physical properties of clayey silt and silty sand on its laboratory electrical resistivity value in loose and dense conditions. *Sains Malaysiana* 46(10): 1959-1969.

Amadei, B. 2012. *Rock Anisotropy and the Theory of Stress Measurements*. Germany: Springer Science & Business Media.

Azman, A.G., Borhan, M.D. & Teh, G.H. 2000. Age, petrochemistry and modelling of the Bukit Mertajam-Kulim granite, Northwest Peninsular Malaysia. *Bulletin of the Geological Society of Malaysia* 44: 139-150.

Baines, D., Smith, D.G., Froese, D.G., Bauman, P. & Nimeck, G. 2002. Electrical resistivity ground imaging (ERGI): A new tool for mapping the lithology and geometry of channel-belts and valley-fills. *Sedimentology* 49: 441-449.

Balasubramanian, A., Sharma, K.K. & Sastri, J.C.V. 1985. Geoelectrical and hydrogeochemical evaluation of coastal aquifers of Tambraparni basin, Tamil Nadu. *Geophysical Research Bulleting* 23: 203-209.

Berge, M.A. 2014. Electrical resistivity tomography investigations on a paleoseismological trenching study. *Journal of Applied Geophysics* 109: 162-174.

Chambers, J., Wilkinson, P., Weller, A., Meldrum, P., Kuras, O., Ogilvy, R., Aumonier, J., Bailey, E., Griffiths, N. & Matthews, B. 2012. Characterising sand and gravel deposits using electrical resistivity tomography (ERT): Case histories from England and Wales. In *Proceedings of the 16th Extractive Industry Geology Conference,* edited by Hunger, E. & Walton, G. pp. 166-172.

Chandra, S., Ahmed, S., Ram, A. & Dewandel, B. 2008. Estimation of hard rock aquifers hydraulic conductivity from geoelectrical measurements: A theoretical development with field application. *Journal of Hydrology* 357: 218-227.

Cheng, K.S., Simske, S.J., Isaacson, D., Newell, J. & Gisser, D. 1990. Errors due to measuring voltage on current-carrying electrodes in electric current computed tomography. *Biomedical Engineering, IEEE Transactions* 37: 60-65.

Chung, K.W., Leman, M.S., Dzulkafli, M.A., Mohamed, K.R., Ali, C.A. & Ab Talib, J. 2017. Gagau group (early cretaceous) sedimentary rock deposited at Sungai Chichir upstream, Terengganu Darul Iman, Malaysia. *Sains Malaysiana* 46(12): 2315-2323.

Cobbing, J. 2000. *The Geology and Mapping of Granite Batholiths.* Heidelberg, Germany: Springer.

Ghani, A.A., Doya, B.M. & Teh, G. 2000. Age, petrochemistry and modelling of the Bukit Mertajam-Kulim granite, Northwest Peninsular Malaysia. *Bull. Geol. Soc. Malaysia* 44: 129-150.

Gobbett, D.J. & Hutchison, C.S. 1973. *Geology of the Malay Peninsula: West Malaysia and Singapore*. New York: John Wiley & Sons.

Gonzaga, G., Leite, M. & Corthésy, R. 2008. Determination of anisotropic deformability parameters from a single standard rock specimen. *International Journal of Rock Mechanics and Mining Sciences* 45: 1420-1438.

Haile, N. 1980. Palaeomagnetic evidence from the Ordovician and Silurian of Northwest Peninsular Malaysia. *Earth and Planetary Science Letters* 48: 233-236.

Hakala, M., Kuula, H. & Hudson, J. 2007. Estimating the transversely isotropic elastic intact rock properties for in situ stress measurement data reduction: A case study of the Olkiluoto mica gneiss, Finland. *International Journal of Rock Mechanics and Mining Sciences* 44: 14-46.

Jasin, B. 2008. Some Permian radiolarians from Bukit Yoi, Pokok Sena, Kedah. *Bulletin of the Geological Society of Malaysia* 54: 53-58.

JMG 2014. *Geological Map of Peninsula Malaysia*. Kuala Lumpur: JMG.

Kearey, P., Brooks, M. & Hill, I. 2002. *An Introduction to Geophysical Exploration.* Oxford: Blackwell Science Ltd.

Khoo, T.T. & Tan, B.K. 1983. Geological evolution of Peninsular Malaysia. In *Proceedings of the Workshop on Stratigraphic Correlation of Thailand and Malaysia* 1: 253-290.

Kneisel, C. 2006. Assessment of subsurface lithology in mountain environments using 2D resistivity imaging. *Geomorphology* 80: 32-44.

Loke, M., Chambers, J., Rucker, D., Kuras, O. & Wilkinson, P. 2013. Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics* 95: 135-156.

Loke, M.H. 2014. 2-day workshop on 2D and 3D electrical resisitivity imaging surveys. Universiti Sains Malaysia.

Loke, M., Wilkinson, P., Uhlemann, S., Chambers, J. & Oxby, L. 2014. Computation of optimized arrays for 3-D electrical imaging surveys. *Geophysical Journal International* 199: 1751-1764.

Loke, M., Wilkinson, P., Tejero-Andrade, A. & Kruse, S. 2015. Optimized arrays for resistivity measurements confined to the perimeter of a survey area. *Near Surface Geoscience 2015-21st European Meeting of Environmental and Engineering Geophysics* 10.3997/2214-4609.201413793.

Mallik, S., Bhattacharya, D. & Nag, S. 1983. Behaviour of fractures in hard rocks-A study by surface geology and radial VES method. *Geoexploration* 21: 181-189.

Mohamad, H. & Roslan, N. 2017. Characterization of aquifer properties in granite in Selangor. *Sains Malaysiana* 46(12): 2331-2338.

Nunes, A.L.L. 2002. A new method for determination of transverse isotropic orientation and the associated elastic parameters for intact rock. *International Journal of Rock Mechanics and Mining Sciences* 39: 257-273.

Panek, T., Hradecký, J. & Silhan, K. 2008. Application of electrical resistivity tomography (ERT) in the study of various types of slope deformations in anisotropic bedrock: Case studies from the Flysch Carpathians. *Studia Geomorphologica Carpatho-Balcanica* 32: 57-73.

Panissod, C., Michel, D., Hesse, A., Joivet, A., Tabbagh, J. & Tabbagh, A. 1998. Recent developments in shallow-depth electrical and electrostatic prospecting using mobile arrays. *Geophysics* 63: 1542-1550.

Ringstad, A.C., Ringstad, C.M. & Ringstad, M.L. 2000. 2D electrical resistivity in a complex geology environment. *Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems.* pp. 1113-1115.

Rucker, D.F., Loke, M.H., Levitt, M.T. & Noonan, G.E. 2010. Electrical-resistivity characterization of an industrial site using long electrodes. *Geophysics* 75: WA95-WA104.

Soupios, P., Georgakopoulos, P., Papadopoulos, N., Saltas, V., Andreadakis, A., Vallianatos, F., Sarris, A. & Makris, J. 2007. Use of engineering geophysics to investigate a site for a building foundation. *Journal of Geophysics and Engineering* 4(1): 94-103.

Stan, D. & Stan-Kłeczek, I. 2014. Application of electrical resistivity tomography to map lithological differences and

subsurface structures (Eastern Sudetes, Czech Republic). *Geomorphology* 221: 113-123.
Sudha, K., Israil, M., Mittal, S. & Rai, J. 2009. Soil characterization using electrical resistivity tomography and geotechnical investigations. *Journal of Applied Geophysics* 67: 74-79.
Van Heerden, W. 1983. Stress-stain relations applicable to overcoring techniques in transversely isotropic rocks. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics* 20(6): 277-282.
Wilkinson, P., Loke, M., Chambers, J. & Oxby, L.S. 2013. Computation of optimized arrays for 3-D electrical imaging surveys. *Geophysical Journal International* 199(3): 1751-1764.
Worotnicki, G. 2014. CSIRO triaxial stress measurement cell. *Comprehensive Rock Engineering* 3: 329-394.
Zhu, T., Feng, R., Hao, J.Q., Zhou, J.G., Wang, H.L. & Wang, S.Q. 2009. The application of electrical resistivity tomography to detecting a buried fault: A case study. *Journal of Environmental & Engineering Geophysics* 14: 145-151.

John Stephen Kayode
Environmental Technology
School of Industrial Technology
Universiti Sains Malaysia
11800 USM, Pulau Pinang
Malaysia

Mohd Hariri Arifin*
Department of Geology
School of Environmental and Natural Resources Sciences
Universiti Kebangsaan Malaysia
43600 UKM Bangi, Selangor Darul Ehsan
Malaysia

Mohd Nawawi
Geophysics Unit
School of Physics
Universiti Sains Malaysia
11800 USM, Pulau Pinang
Malaysia

*Corresponding author; email: hariri@ukm.edu.my

Received: 23 April 2018
Accepted: 22 February 2019