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Geophysical investigations at the proposed site of the KNUST teaching Hospital building using the 2D and 3D resistivity imaging techniques

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Abstract

Geophysical investigations involving the use of 2D and 3D electrical resistivity imaging techniques have been carried out at the proposed site of the KNUST Teaching Hospital Building in Kumasi, Ghana, to study the nature of the subsurface structure to assess its suitability for the construction of superstructures. Part of the site was an old refuse dump. The main objectives are to determine the depth to the bedrock, and the possible presence of faults, fractures, voids and clay that may pose a danger to the structures that are to be constructed. Twenty eight (28) high-resolution 2D electrical resistivity images were acquired using the Wenner configuration with both electrode and profile separations of 4 m. The roll-along technique was employed to cover the profile length of 200 m which was constant for all the lines. The 2D resistivity data were collated and inverted to produce a 3D image. The 2D and 3D models allowed the location of clay soil, fractures, bedrock and seepage paths from the refuse dump that used to be there. The results showed that the site is suitable for the construction of the proposed KNUST Teaching Hospital.

Keywords: 2D and 3D electrical resistivity imaging (ERI), continuous vertical electrical sounding (CVES), ABEM lund imaging system, apparent resistivity, pseudo sections.

INTRODUCTION

It is a well known fact that subsurface investigations involving the use of geophysical techniques are important for assessing the suitability of an area for the construction of buildings, bridges and dams among others. Many high-rise buildings have been springing up in Ghana during the past three decades. There have also been reports of collapsed buildings undertaken in the country. It is common knowledge that most of these buildings have been constructed without prior geophysical investigations to determine the nature of the subsurface structure.

Paramount to the construction of any building is the suitability of the geology of the site. Most buildings are constructed on soil that has inadequate bearing capacity to support the weight of the structure. Furthermore, the near-surface soils may consist of expansive clays that shrink or enlarge as the moisture content is changed. Movement of foundation may occur if the clay moistening

and drying is not uniform. Subsurface geological features such as fractures, voids, nearness of the depth to bedrock, nearness of the water table to the surface are among the inconveniences that pose constraint to building constructions especially to their foundations.

The use of the geoelectrical method as an effective tool for gaining knowledge into the subsurface structure, in particular, for identifying anomalies and defining the complexity of the subsurface geology is fast gaining grounds (Soupois et al., 2007; Colangelo et al., 2008; Lapenna et al., 2005). In recent times, much attention is being paid to the electrical resistivity imaging (ERI) method (Griffiths and Baker, 1993; Loke and Barker, 1996; Giano et al., 2000; Schmutz et al., 2000), which provides a high spatial resolution with a relatively fast field data acquisition time and is low in cost (Lapenna et al., 2005). It is more of a natural counterpart to the near-surface seismic reflection method and therefore may play a more significant role in the geophysical exploration of many subsurface investigations.

In the last decade, the involvement of geophysics in

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civil and environmental engineering has become a promising approach. Geophysical methods are implemented in a wide range of applications ranging from ground investigations in building constructions to the inspection of dams and dikes (Klimis et al., 1999; Luna and Jadi, 2000; Othman, 2005; Soupios et al., 2005; 2006; Venkateswana et al., 2004), aiming towards the exploration of geological structures and the determination of the physical parameters of the rock formations. In engineering geophysics, the question of the quality of building foundations is frequently addressed in the very late stages, when earthquake damage is either observed or expected (Delgado et al., 2000a; 2002; 2000b; von Seht and Wohlenbug, 1999; Parolis et al., 2001). In the case of building construction, geophysics can be applied for exploration purposes to provide useful information regarding the early detection of potentially dangerous subsurface conditions. The sources of hazards in civil engineering disciplines result essentially from undetected near-surface structures, such as cavities and/or inhomogeneities in the foundation geomaterials. Information related to the local soil conditions is vital for risk assessment and mitigation (Soupois et al., 2007).

The procedure for obtaining subsurface information is divided into two broad categories: indirect and direct methods. Indirect methods include aerial photography, topographic map interpretation and the study of existing geological reports, maps, and soil surveys. Direct methods comprise of the following modules: (a) geologic field reconnaissance, including the examination of in situ materials, man-made structures, groundwater level and exploration of shafts, (b) application of modern geophysical techniques for mapping subsurface structures, (c) borings, test pits, trenches and shafts from which representative disturbed and/or undisturbed samples of the in situ materials may be obtained and analysed and (d) simple geotechnical field tests, such as the standard penetration test (SPT), which can be correlated with other engineering parameters (Soupois et al., 2007). Some of the geophysical methods that can be applied in the direct method for mapping subsurface structures include: ground penetrating radar (GPR), seismic, electromagnetic terrain conductivity (Ward, 1990), electrical resistivity tomography (ERT), 2D and 3D electrical resistivity imaging (ERI). The 2D and 3D electrical resistivity imaging can be carried out using the electrical resistivity method with the necessary softwares for processing of the acquired field data. The use of 2D and 3D geoelectrical resistivity imaging to address a wide variety of hydrological, environmental and geotechnical issues is increasingly popular. The subsurface geology in environmental and engineering investigations is often subtly heterogeneous and multi-scale such that both lateral and vertical variations of the subsurface properties can be very rapid and erratic (Aizebeokhai et al., 2011). The use of vertical electrical sounding is grossly inadequate to map such complex and multi-scale

geology. 2D geoelectrical resistivity imaging, in which the subsurface is assumed to vary vertically down and laterally along the profile but constant in the perpendicular direction, has been used to investigate areas with moderately complex geology (Griffiths and Barker, 1998; Dahlin and Loke, 1999; Olayinka and Yaramanci, 1999; Amidu and Olayinka, 2006). But subsurface features are inherently 3D and the 2D assumption is commonly violated for such heterogeneous subsurface. This violation often leads to out-of plane resistivity anomaly in the 2D inverse models which could be misleading in the interpretation of subsurface features (Bentley and Gharibi, 2004; Gharibi and Bentley, 2005). Thus, a 3D geoelectrical resistivity imaging which allows resistivity variation in all possible directions should give more accurate and reliable inverse resistivity models of the subsurface, especially in highly heterogeneous cases (Aizebeokhai et al., 2011).

The use of 3D electrical resistivity techniques for conducting surveys have been presented by Loke and Barker (1996a). Some of the demonstrated electrode configurations used for the accomplishment of 3D which include the use of pole-pole (Li and Oldenburg, 1994; Loke and Barker, 1996; Park, 1998) and pole-dipole (Chambers et al., 1999; Ogilvy et al., 1999) arrays have been reported. Square and rectangular grids of electrodes with constant electrode spacing in both x- and y-directions, in which each electrode is in turn used as current electrode and the potential measured at all other electrode positions, were commonly used. But these methods which allow the measurements of complete 3D data sets are usually impractical due to the length of cables, the number of electrodes and the site geometry involved in most practical surveys (Aizebeokhai et al., 2011). Also, the measurement of complete 3D data sets using the square or rectangular grids of electrodes is time consuming and cumbersome in surveys involving large grids. This is because the number of possible electrode permutations for the measurements will be very large.

To reduce the number of data measurements as well as the time and effort required for 3D geoelectrical resistivity field surveys, a cross-diagonal surveying technique in which apparent resistivity measurements are made only at the electrodes along the x-axis, y-axis and 45° diagonal lines was proposed by Loke and Barker (1996a). The cross-diagonal surveying method also involves very large number of independent measurements for medium to large grids of electrodes. Hence, the measurement of 3D data set using cross-diagonal technique is time consuming, especially if a single channel or a manual data acquisition system is employed. The inversion of these large volumes of data is often problematic because the computer memory may not be sufficient for the data inversion. In contrast to the cross-diagonal surveying method, a set of orthogonal 2D lines (Bentley and Gharibi, 2004; Gharibi and Bentley, 2005; Aizebeokhai and Olayinka, 2009) which allow

flexible survey design, choice of array and easy adaptability to data acquisition systems have been used for 3D geoelectrical resistivity imaging.

Electrical resistivity surveying is now increasingly being used in detecting fractures and cavities in the subsurface, waste sites characterization, geotechnical investigations of buildings, roads, dams and other construction sites, identifying and locating subsurface utilities, delineating archaeological features and monitoring pollution in the ground (Gopalan et al., 1999). There are many electrode configurations designed for collection of geoelectrical resistivity data, but the use of a particular configuration depends on the particular geological situation and the research interest. The most commonly used electrode arrays include Wenner, Schlumberger, dipole-dipole, pole-pole and pole-dipole arrays.

Traditionally, electrical resistivity surveying was limited to either delineating the variation of apparent resistivity over a surface or compiling quasi-2D sections from a rather limited numbers of vertical electrical soundings (VES). The use of multi-electrode/multichannel systems for data acquisition in geoelectrical resistivity surveys has led to a dramatic increase in field productivity as well as increased quality and reliability of subsurface resistivity information obtained. Initially, multi-electrode systems with manual switching (Barker, 1981) were used before the emergence of computer-controlled multi-electrode/multichannel systems with automatic measurements and data quality control, which has tremendous impact on the quality of the data and the speed with which they are collected. Intelligent multi-electrode with built-in preamplifiers, analog-to-digital converters, and digital transmission lines can now be effectively used for data acquisition. Multi-channel transmitter and receiver systems are now being used in simultaneously carrying out series of measurements (Stummer and Maurer, 2001; Auken et al., 2006).

This paper reports on geophysical investigations that have been carried out at a site for the construction of the proposed KNUST Teaching Hospital Building. The site is an old refuse dump and therefore detailed subsurface investigations are needed to obtain information on the depth to bedrock, the presence of fractures, faults, voids and clay, which are important in characterizing the suitability of the area for building purposes. The research was carried out using the multi-electrode system based on the Wenner electrode configuration.

As many as 28 profile lines were investigated at the site using the ABEM Lund Imaging System for the data acquisition. The data inversion method proposed by Loke and Baker (1996) was carried out using the RES2DINV and RES3DINV softwares. The 2D and 3D resistivity models generated were interpreted to determine

the suitability of the area for building purposes.

Geology of the area

The site for the proposed building of the KNUST Teaching Hospital forms part of a much larger KNUST campus that is located within the Kumasi Metropolis and centered on latitude 6° 40' 00" N and longitude 1° 37' 00" W. Much of the Kumasi area features a dissected plateau, probably representing a mid to late Tertiary peneplain, with elevations in the range of 225-300 m above mean sea level (Griffis et al., 2002). There are also a number of rounded and flat-topped hills that crest at elevations of 400-460 m above sea level; these hilltops appear to represent an earlier mid to early Tertiary, regional erosional surface (Griffis et al., 2002). Most of the area is covered by secondary forest and cultivated farms, which are widespread due to the relatively dense population.

The Kumasi Metropolitan area is dominated by the middle Precambrian rocks and forms part of the Eburnean Plutonic Suite (formed approximately within the upper and lower age of 2.172 and 2.116 million years ago) where it mainly composes of the biotitegranite and minor granodiorite and K-feldspar porphyritic rocks (Figure 1). The geology of the area is based mainly on the following published geological maps: Moon (1962) and Kesse (1972). The Birimian sequences in the area are characterized by a transition in the sedimentary facies from the central part of the basin to the margins. Sediments deposited in the central portion consist of a thick sequence of dark grey to black argillites that are interbedded with subordinate siliciclastic metasediments. The argillites grade laterally away from the basin centre into a thick sequence of interbedded argillite/volcaniclastic units and to volcaniclastics interbedded with subordinate argillites, talus and volcanics. Moon (1962) reports of the occurrence of a narrow (up to 3 km wide) belt underlain by interbedded volcaniclastic and coarse arenaceous sediments (grewackes, arkose, conglomerates, and quartzite).

Griffis (1998) notes that these clastic and volcaniclastic units feature high radiometric K levels and appear to be somewhat distinctive from most of the typical interbedded volcaniclastic and marine sedimentary units as well as from the Tarkwaian clastic sediments. The Kumasi granitoid complex (Kesse, 1972) dominates much of the basin area and contains large roof pendants of metasedimentary schists. This massive intrusive complex is basin-type granitoid, which ranges in composition from intermediate (granodiorite/tonalite) to more felsic (granite) phases. The very existence of the Precambrian rock has led to the development of the construction industry in the metropolis.

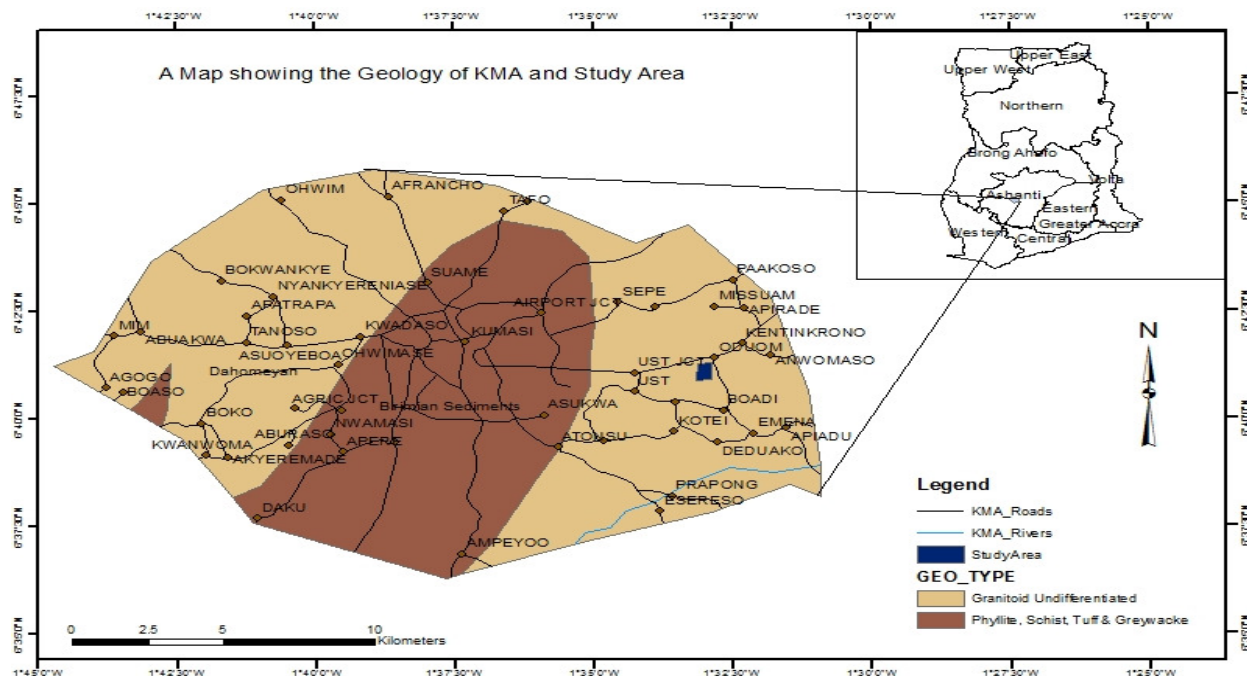


Figure 1. Geological map of Kumasi Metropolis showing the project area in black (Geological Survey Department (GSD), Accra, Republic of Ghana, 2009)

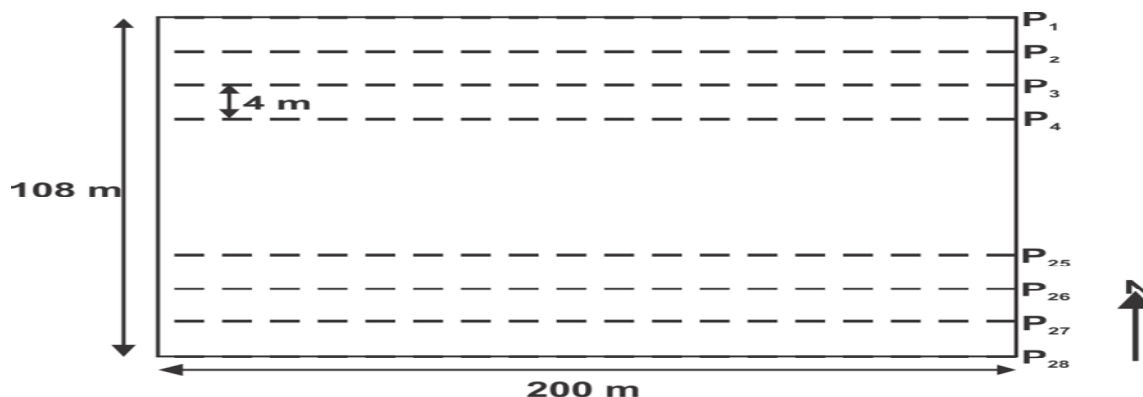


Figure 2. Sketch of the 2D profiling lines in the east – west direction with inter-profile separation of 4 m

MATERIALS AND METHODS

2D and 3D electrical resistivity imaging

Electrical Resistivity Imaging (ERI) is a geoelectrical method that is used to obtain high-resolution 2D and 3D images of the complex geology of the subsurface (Griffiths and Baker, 1993). The ERI can be carried out during field work by using different electrical configurations (such as Wenner, Schlumberger, pole-dipole, and gradient) placed at the surface to send the electric currents into the ground and to measure the generated voltage signals. Technically, during an electrical resistivity measurement, the current is injected into the ground via two electrodes and the potential drop

is measured between two other electrodes in line with the current electrodes (Sharma, 1993).

Continuous Vertical Electrical Sounding (CVES), which combines lateral coverage with vertical data acquisition, was the applied resistivity imaging technique. The multi-electrode ABEM Lund Imaging System was used in the lay-outs, employing the technique of roll-along during the cause of the electrical resistivity measurements. In all, 51 electrodes were used for the multi-electrode system in the Wenner array with electrode spacing of 4 m. From the study area measuring 200 x 124 m², a total of 28 profile lines were obtained with inter-profile spacing of 4 m with each profile line measuring 200 m as shown in figure 2.

After the data collection, transformation of the appa-

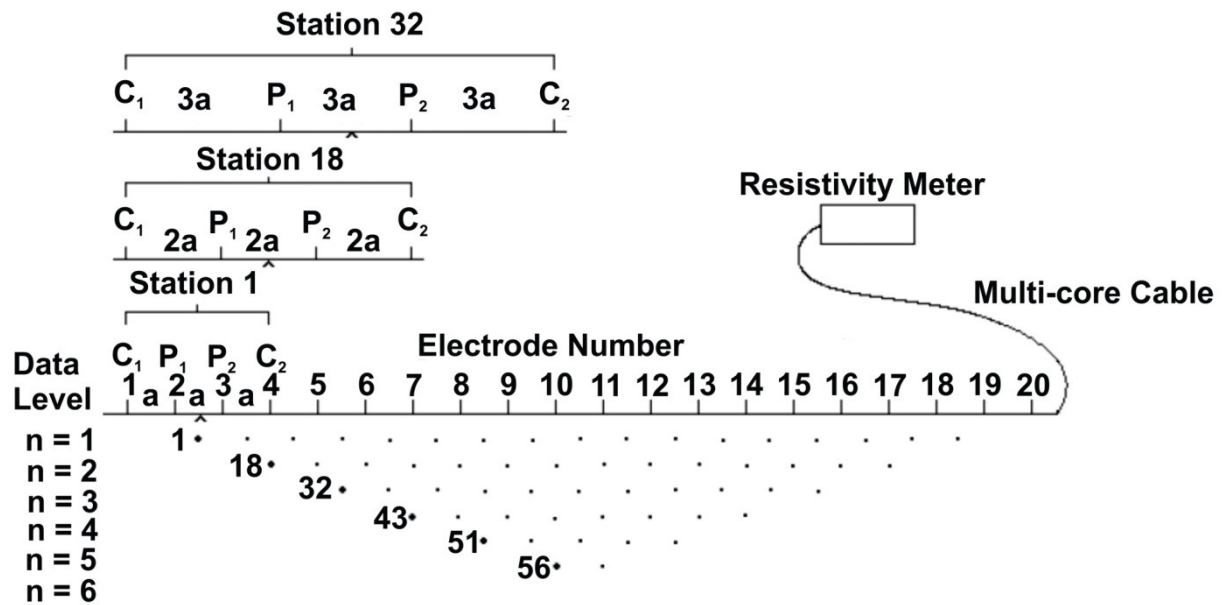


Figure 3. Sketch of the electrodes for the 2D electrical resistivity survey and the sequence of measurements for building the pseudo-section [Loke, 2011]

rent resistivity pseudosection into a model of the subsurface resistivity distribution was achieved using the method proposed by Loke and Baker (1996). RES2DINV algorithm was used in the data processing, which generated the two-dimensional (2D) models. The 2D resistivity model was obtained by applying the Robust (L1-norm) inversion method to the measured data (Loke et al., 2003). The resistivity model fitness was evaluated by the mean residual value, which is a comparison between the resistivity values calculated on the model and the measured apparent resistivity. In addition to the inversion routine, the user defined logarithmic contour interval was applied to all the profile lines in order to have even contour values and spacings for easier comparison of the profile lines.

The electrical resistivity imaging (ERI) system is a multi-electrode system and the spacing between the electrodes remains the same, but the separation between the potential and the current electrodes varies depending on the electrode configuration. The electrodes are arranged on a line and are connected to a multi-core cable which is connected to a selector and then to the resistivity meter or from the cable to the resistivity meter directly. The resistivity meter automatically determines the separation and also which electrodes are to be used as current pair and potential pair. The meter measures the apparent resistivities by using a range of different electrode separations and midpoints (figure 3). The apparent resistivity values are normally presented in pictorial form using pseudo-sections (Figure 3) which give approximate pictures of the subsurface resistivity distributions. The roll-along survey technique is employed when there is a limited number of electrodes and cables

to extend horizontally the area to be covered by the survey.

Data Acquisition and Processing

The multi-electrode ABEM Lund Resistivity Imaging System was used to carry out the electrical resistivity measurements on 28 parallel profiles separated by 4 m on the proposed site of the KNUST Teaching Hospital Building. The system operates automatically once the geometrical parameters (array type, electrode separation and minimum current) are set. Each of the 2D traverses was 200 m in length covering an area of 200 x 108 m². The Wenner array using 41 electrodes connected to four 40 m long multi-core cables with electrode separation of 4 m was used for the measurements. Before each set of measurements, we performed the electrode check to ensure that all the electrodes were conducting. The data acquisition process is completely controlled by software. After completion of the measurements for the 160 m long set-up array, the roll-along technique was employed in order to extend horizontally the entire length of the profile (200 m) and continuous coverage of the subsurface.

The processing of the electrical resistivity measurements was done using the Res2DINV software. Elevation corrections were not carried out because the area surveyed was almost flat. The data was first filtered to remove bad datum point and then inverted to estimate the true resistivity structure of the subsurface. The L1-norm (robust) inversion technique was used to allow the modeling of relatively sharp changes in resistivity because the inversion algorithm aims to minimize the

absolute value of data misfit (Loke et al. 2003). Model refinement option of the "Inversion" menu was used to take care of the large resistivity variations near the ground surface. With this option, the program automatically reduces the unit electrode spacing it uses by half of that given in the data. We also use the user defined logarithmic contour intervals option for easier comparison of the images (Loke, 2011).

The 2D traverses were merged together to produce a single 3D data set. This was done by collating the measured 2D profile lines data to a 3D data format that can be read by the RES3DINV computer code using the RES2DINV software. The RES3DINV software was used to process the collated data, which generated the 3D model of the subsurface resistivity distribution.

RESULTS AND DISCUSSION

The obtained electrical resistivity images of the subsurface of the 28 parallel traverses spaced 4 m apart are presented as models in figures 4, 5, 6 and 7. The root mean square errors obtained in the inverted models were between a minimum of 1.06 to a maximum of 2.30 %. There is a good correlation between the subsurface images. The models show a range of both low resistivity and relatively high resistivity zones. The low resistivity values (i.e. $< 150 \Omega\text{m}$) on profiles 1 and 2 between 40 and 90 m on the surface to a depth of about 3 m have been interpreted to be due to seepages from the refuse dump that used to be there. These low resistivity regions resulting from the seepages were confined to the near-surface because of the high resistivity body with resistivity $> 1000 \Omega\text{m}$. The body or structure could probably be an impermeable material beneath that zone. The chemicals seeped to a greater depth on profiles 3 and 4 because of the absence of the high resistivity body as observed on these profiles (Figure 4). The other low near-surface resistivities areas are: between 100 and 110 m on profiles 10 – 13 (Figure 5), beginning of profile 15, 16, 17, 20, 21 and 22 (Figs. 5 and 6) and around 160 m on profiles 15 and 16 were all due to seepages from the patches of refuse that used to be there.

The patches of moderately low resistive zones found at isolated places on some of the models are as a result of some portions of the profile lines lying across water ways and others crossing swampy areas. Portions of the earth with these low or saturated features are as a result of the high moisture content from water, or in the case of the refuse dump site, chemicals from the materials dumped at the site. The effect of these shows a high concentration of the range of resistivity values grouped at a place with a rapid change in resistivity values. The effect in a hard zone is a gradual change or alteration of the competent rock to a weaker rock forming a weaker geological zone.

The 2D electrical resistivity models show that beneath the region of low resistivity values found in isolated

places at depths of 3 – 7 m on most of the geo-electrical inverse images are the granites which have high resistivities. The resistivities of the granites range from about 400 to over 2000 Ωm .

Weathering probably accounts for most of the changes in the formation of the bedrock, with high resistivity values or zones gradually changing into lower resistivity zones (profiles 3 - 6, 13 – 18, and 20- 28). The most resistive part of the area investigated was the northeast where the resistivity value was $> 1200 \Omega\text{m}$; that is the zone where the granites are more consolidated and weathering is minimal. Generally, the degree of weathering of the granites decreases westwards and southwards resulting in increasing resistivity and consolidation of the subsurface in these directions. The exceptions are in profiles 3 - 5 and 12 – 17 where the middle portion of the images show lower resistivities than the ends as a result of greater weathering in these areas. Although the most resistive and consolidated part of the subsurface investigated is beneath profiles 1 and 2, the expanse of the land there is smaller considering that the inter-profile separation is 4 m. The southern part would favour the construction of heavy buildings for the proposed Teaching Hospital.

The 3D image model block was sliced into 10 layers at varying depth distance beginning from the surface to the achieved depth. The inverse 3D model in Figure 8 shows the horizontal sections of the model obtained after 5 iterations. The 10 layer sections show the various geological depths at the survey site beginning from the surface deep into the ground. The heterogeneous earth can be seen very much clearly in the 3D model compared to that of the 2D resistivity models. The first and second layers show complex subsurfaces which are more heterogeneous compared to layer 3 and 4. The heterogeneous nature of these layers could be due to the effect of the numerous seepages of chemicals from the patches of refuse dump sites and probably the removal of soil samples from one place to another at the site from the excavation works prior to the commencement of the construction work. Layer 1 and 2 indicate a subsurface of both low and high resistivity zones, where the low resistivity zones probably correspond to the seepages from the refuse that used to be there and some few areas being waterlogged. The high resistivity values are more of the highly weathered basement granitoids. The layers 3 and 4 show an area of less complexity compared to the previous layers and a zone depicting consolidation of the granites. The subsequent layers show clearer and distinct individual geological structures of varying high resistivity inter-laced in each other. (Figure 7 and 8)

The patches of low resistivity values which were observed on the surface of the 2D models were evident on the surface of the 3D model as well as the moderately high resistivity values of about 500 Ωm that characterize the middle portion of profiles 3 - 6 (Figure 4) and 13 – 18 (Figure 5 and 6). The 2D and 3D resistivity values depict an increase in resistivity with depth.

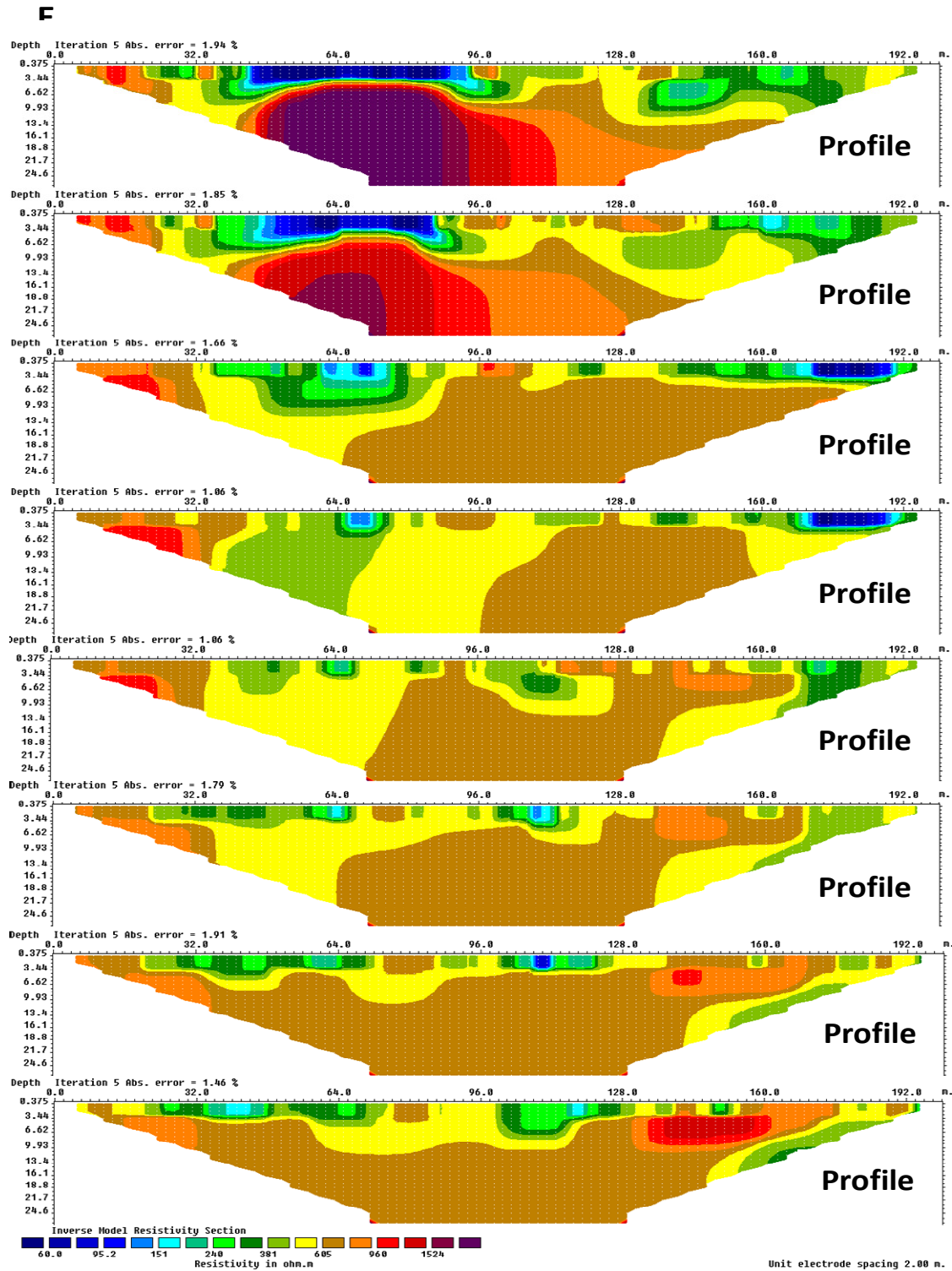


Figure 4. 2D resistivity models for parallel profile lines 1 to 8 acquired at the proposed KNUST Teaching Hospital Site with inter-profile separation of 4 m .

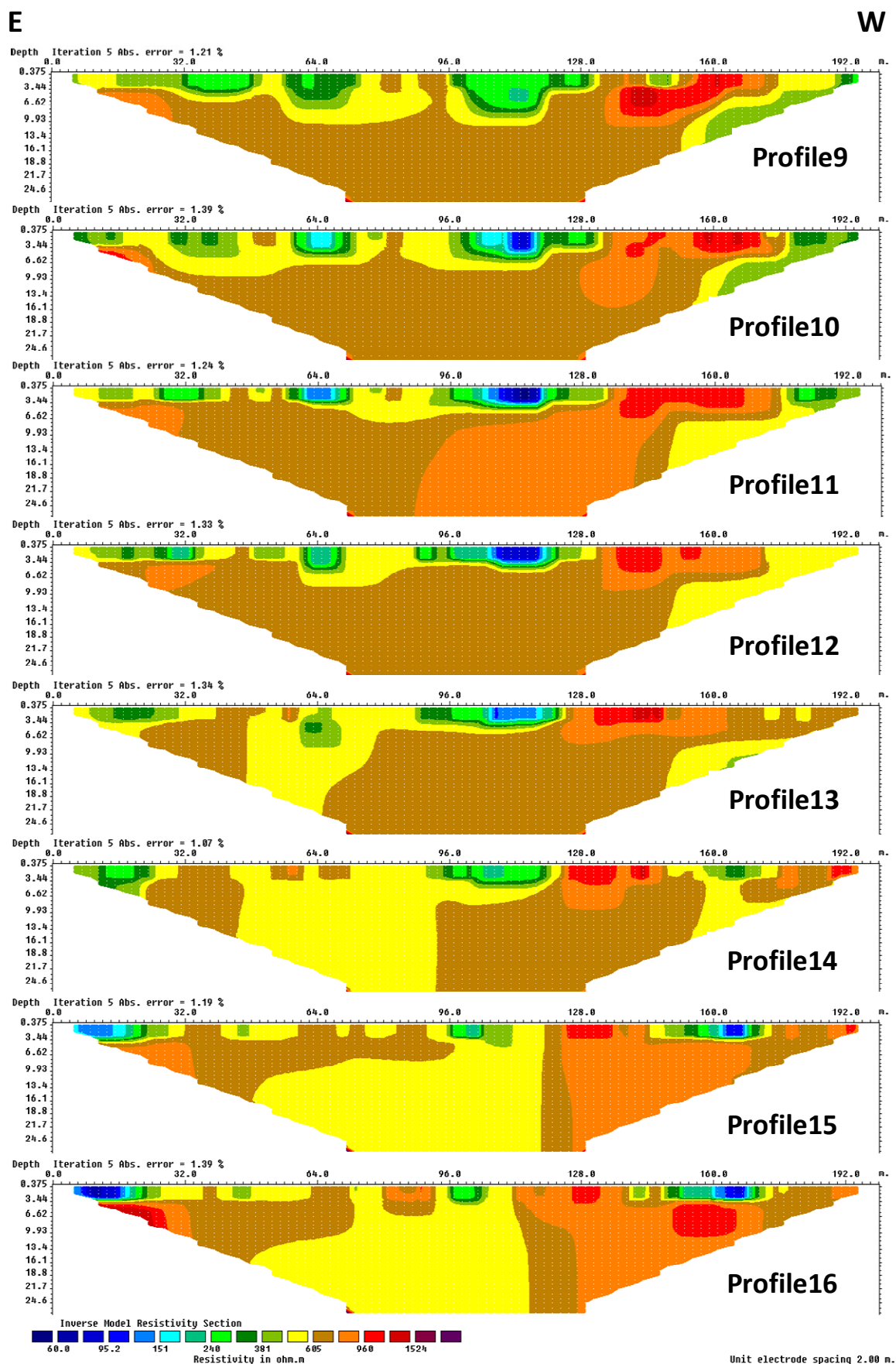


Figure 5. 2D resistivity models for parallel profile lines 9 to 16 acquired at the proposed KNUST

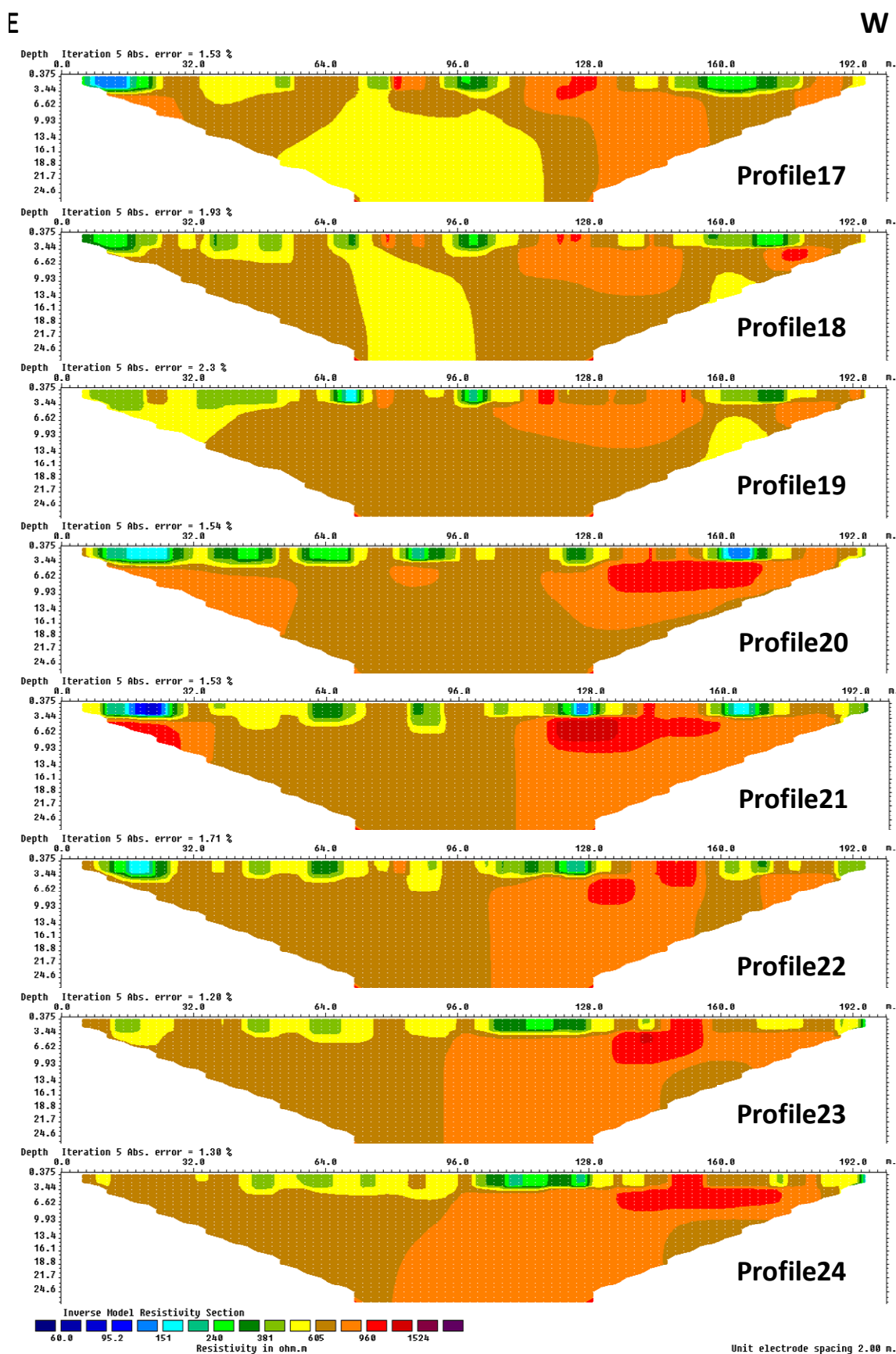


Figure 6. 2D resistivity models for parallel profile lines 17 to 24 acquired at the proposed KNUST Teaching Hospital Site with inter-profile separation of 4 m using the robust inversion technique

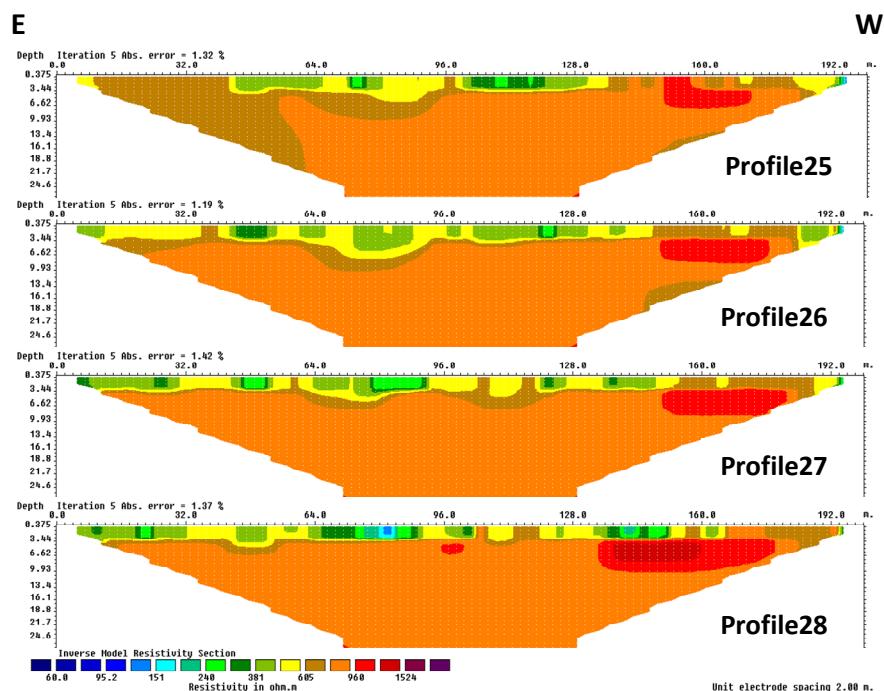


Figure 7. 2D resistivity models for parallel profile lines 25 to 28 acquired at the proposed KNUST Teaching Hospital Site with inter-profile separation of 4 m using the robust inversion technique

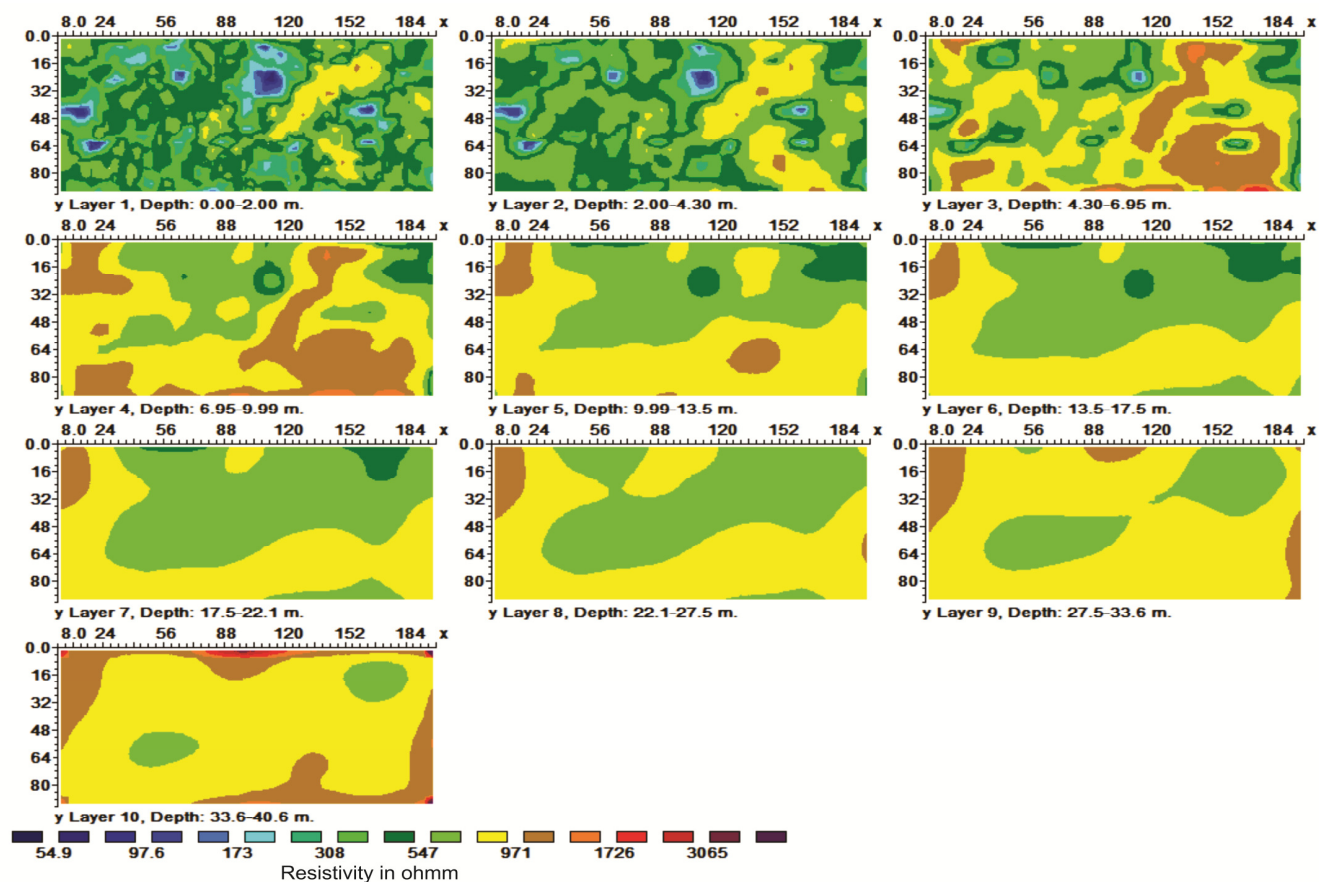


Figure 8. 3D inversion model of the electrical resistivity imaging profiles, acquired at the proposed KNUST Teaching Hospital Site

CONCLUSIONS

The electrical resistivity imaging (ERI) method was used successfully to investigate the suitability of the proposed site earmarked for the building of the KNUST Teaching Hospital. The geophysical investigations were conducted to determine any subsurface geological deficiency that may pose a problem for the building. The geophysical data were interpreted with the help of the known geological data of the area. Successful delineation of the various features that make up the complex geology of the area has been achieved as can be seen in the 2D and 3D image models. The bedrock was found to be at a depth 4 to about 7 m. Fractures, faults and voids were not found but some small amount of clay was delineated at a small portion which did not pose any danger for constructional purposes. It was found that the southern portion of the study area is more suitable for the construction of heavy buildings than the northern portion.

From the success achieved in this work, the ERI method can be combined with other geotechnical tools to investigate constructional site prior to commencement of work. The ERI method apart from its non-invasive nature in imaging the earth, has the advantage of being a powerful imaging tool for complex geology; it has fast field data acquisition characteristics, and is low cost and has much less labour requirement.

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