



**APPLICATION OF GEOPHYSICAL METHODS IN
FOUNDATION INVESTIGATION FOR CONSTRUCTION
PURPOSES AT OLKARIA (V) FIELDS, KENYA.**

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ABSTRACT

Geophysical methods were used in structural foundation investigation at Olkaria (V) field in Kenyan rift valley prior to the construction works. Geophysical techniques were of preference because they are faster, cost effective and non-destructive compared to conventional way such as boring and drilling which are expensive, invasive and provide information in discrete area. Geophysical investigations provide a wider picture of the subsurface that aid in evaluation of ground fitness for construction purposes. The objective of this investigation was to determine the depth to bedrock that forms a firm foundation for development purposes. Electrical resistivity and seismic methods were used in ground assessment for its suitability in structural development.

Data was collected using electrical resistivity imaging system, geographical positioning system (GPS), receiver and seismograph. The RES2DINV and Geometrics SeisImager Software respectively were used to process results obtained from these investigations. The methods used gave results that are significant in the preliminary stages of site assessment for foundation works. The techniques probe the depth to the bedrock and reveal weak soils zones. The analysis and interpretation of geophysical data provide a better understanding into the subsurface geology for foundation works.

Compact rock materials were observed from a depth of 14m below ground level extending down to greater depths. Further, the area was characterized by weak Silty material, which has low bearing and consolidation ability. Such materials are prone to frequent washout under conditions of percolating waters hence require utmost care during the placement of engineering structures. Utilization of piles is necessary and should be anchored to a depth greater than 14m below ground level such that they rest directly on the competent bed. In-situ compaction should go before utilization of reinforced concrete amid the development of shallow foundation to achieve the maximum compaction limits due to the anticipated load of the proposed infrastructure. Equally, excavation of the top soil is necessary and thereafter refilling with competent material such as gravel and laterite in order to have a strong basement.

Key words: *Electrical resistivity, Seismic refraction, Shear wave velocity and Geotechnical exploration.*

1.0 Introduction

The principle target of this study is to describe the use of electrical resistivity and seismic method in foundation investigation at Olkaria (v) fields, with the perspective of determining the depth to bedrock that forms a firm foundation for development purposes. The proposed Olkaria V power plant (Figure 1.1) is found inside the Olkaria Domes Production Field inside the Olkaria Geothermal area which is the primary point of this investigation. The Olkaria Domes Production field aids the Olkaria (IV) power plant, producing 140 MWe and a progression of wellhead generators at different wells inside the field. The volcanic and basic improvement of the Kenya Rift has been contemplated for a long time utilizing chronologic and litho-stratigraphic relationship strategies (Thompson and Dodson, 1963; Baker and Wohlenberg, 1971). It is well

understood that volcanic activities began amid the early Miocene with broad basaltic and phonolitic volcanism on the top of the raised dome.

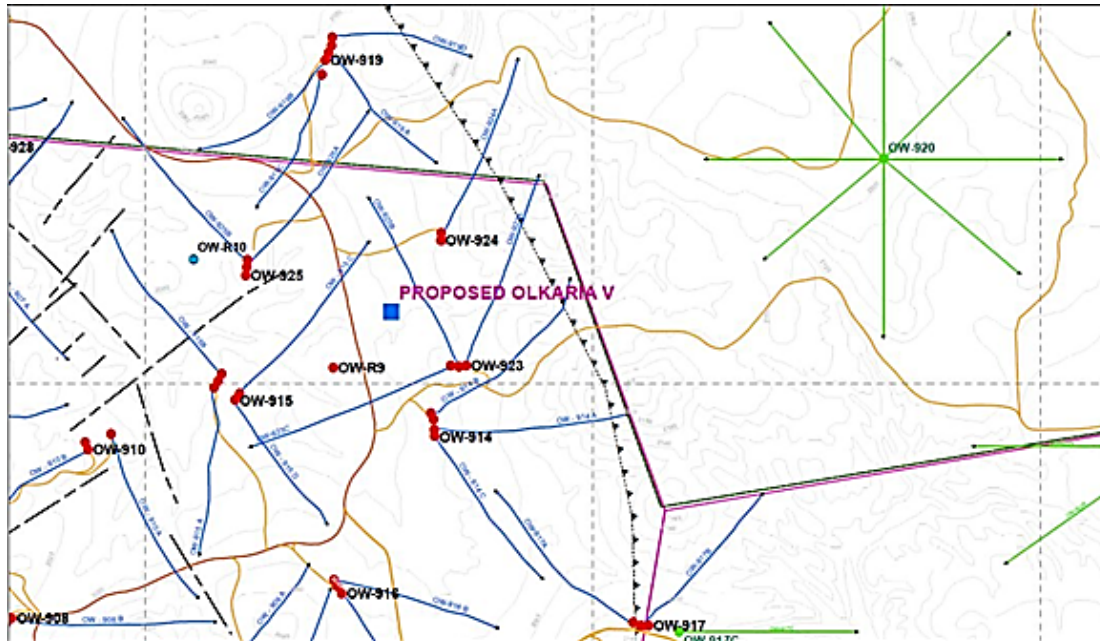


Figure 1.1: Map of the proposed Olkaria V power station (KenGen Internal Report, 2014)

This paper provides fundamental information on the subsurface geology using electrical resistivity tomography and seismic methods that were deployed at Olkaria geothermal fields. These methods provide subsurface information with little cost involved and wider area of coverage for a short time. Further they identify anomalies and describe the complexity of the subsurface geology with ease compared to conventional methods such as boring and drilling that takes a very long time to acquire data and costly. In engineering works, undetected subsurface structures such as faults, fractures and inhomogeneity in geological material can adversely affect the integrity of the foundation structure. Thereby information regarding the bearing ability of soil is vital for risk assessment and thereafter mitigation. The surveys will evaluate the physical properties of the subsurface in terms of soil competence, depth to bedrock and the lithological sequence.

Foundation examination is a critical program in building and designing structures that ought to be undertaken prior to any engineering works. Geophysical techniques such as seismic and resistivity are utilized for the achievement of a better foundation investigation. Electrical resistivity review in site examination is a prime decision due to cheap cost that is included and the way that it saves time, simple to complete and can be used to decide land structures. (Al-Sayed

and El-Qady 2007). It can be used in a wide area within a short time and the information acquired can be interpreted with ease.

Geophysical strategies are executed in a wide scope of utilizations extending from ground examinations in building developments aiming towards the investigation of land structures and the assurance of the physical parameters of the rock formations. Because of building development, geophysics can be applied for investigation purposes to give helpful data in regards to the early identification of conceivably unsafe subsurface conditions. This enables the engineers to design the structure bearing in mind the foundation defects and the mitigation measures.

Geophysical investigation for development purpose requires analyzing soil properties and related features such as faults dispersion and bedrock properties on and beneath the investigation site. The investigation helps in understanding the subsurface on which the engineering works is done. It in-cooperates evaluating the hazards the features may have to property and people. Weak regions with faults and fractures are avoided for a better base establishment. Usually this problem is articulated in regions where the superimposed materials are non-homogeneous in nature. Geophysical methods in ground investigation for building construction aim at exploring the subsurface structures and determining the physical parameters of the rock formation.

In understanding the subsurface using geophysical methods, the physical properties of the underlain material are of major concern. The physical properties measured by geophysical methods include; acoustic velocity, electrical resistivity and density. The parameters of interest in the study of these physical properties are depth to bedrock and rock density.

Electrical resistivity technique is utilized in outlining the different litho units at a proposed building site. (Omowumi 2014). These measurements taken show layers of rocks from top layer down with varying conductivity. The electrical current injected into the ground penetrates through masses of rocks with different conductivity levels. These rocks have been altered and bare different water content and mineralogy making them to have low or high resistivity values. In the study of the subsurface this resistivity values become of interest as they give the rock arrangements depending on the resistivity of each rock. This technique is able to show compact masses of rocks that are dry and unconsolidated material that have water content. Solid rock materials have high resistivity values while loose unconsolidated materials have low resistivity. The sources of perils in structural building disciplines result from undetected close surface

structures, for example, cavities and inhomogeneities in the establishment geo-materials. Data identified with the local soil conditions is fundamental for hazard evaluation and mitigation (Soupois et al., 2007). Soil conditions such as wetness and dryness play a key role in understanding the bearing ability of the foundation. The sources of risks in structural designing controls result from undetected close surface structures, for example in-homogeneities in the establishment geo-materials. An essential factor frequently considered in foundation investigation is the water table as it induces unsteadiness of the overlying structure (Othman, 2005). The utilization of the geo-electrical technique is a successful instrument for studying into the subsurface structure, specifically, for distinguishing abnormalities and characterizing the multilayered nature of the subsurface topography (Soupois et al., 2007; Lapenna et al., 2005). The resistivity of ordinary rocks, soil materials and compounds (Keller and Frischknecht 1966, Daniels and Alberty 1966) as in (Figure 1.2) demonstrates the conductivity in these rocks relying upon their resistivity. The resistivity of these rocks is dependent on the dimension of cracks, and the dimension of the cavities occupied with ground water. Molten and metamorphic rocks normally have high resistivity regards. Thus a given rock type can have an immense extent of resistivity, subject upon its wetness or dryness. This feature is useful in the distinguishing proof of crack zones and other weathering features, for instance, in structure and groundwater inspections.

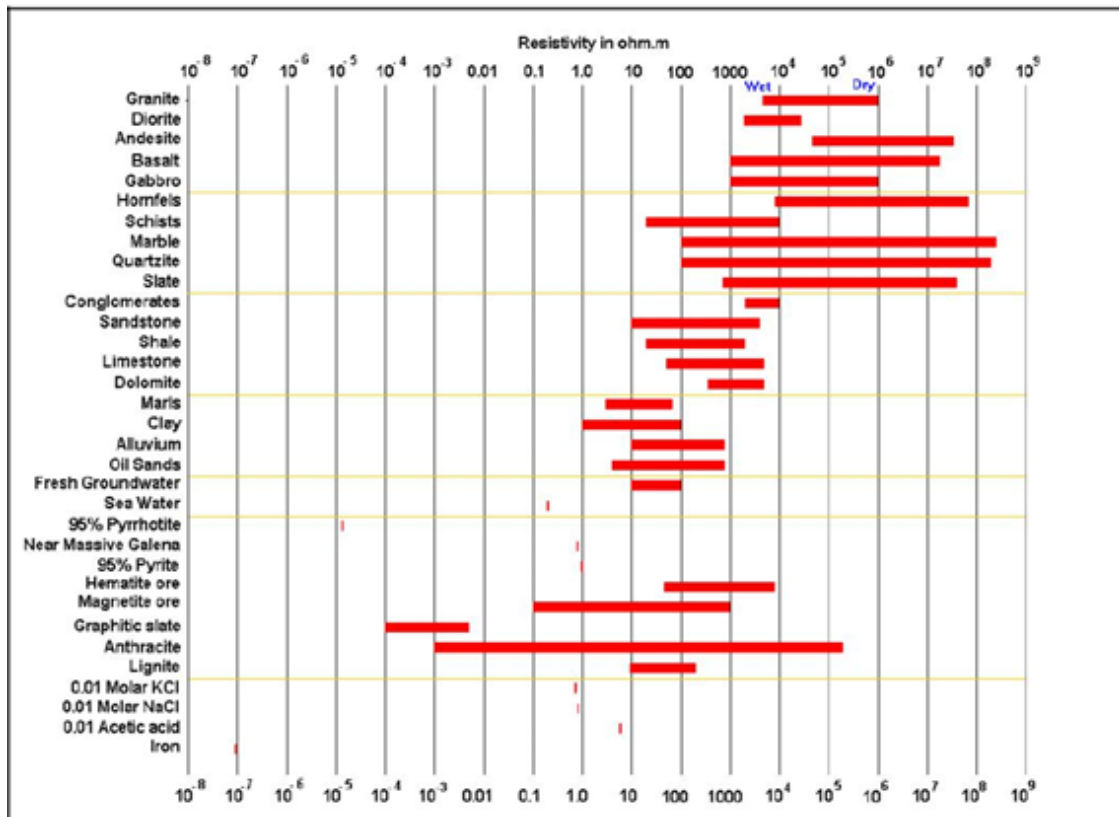


Figure 1.2: The resistivity of rocks, soils and minerals (Daniels and Alberty 1966)

1.1 Resistivity Theory

Electrical tomography technique aims to build up a picture of the electrical properties of the subsurface by passing an electrical current along many different paths and measuring the associated voltage (R. D. Barker 1997). Current flows through the subsurface which consist of layers with varying resistivity. From one material to another variation in measured resistivity provide useful information on the physical property of the subsurface. From these measurements, the true resistivity of the subsurface can be estimated. Electrical resistivity of rocks is measured in ohm-meters (Ω -m) which is associated to various geological parameters such as mineral and fluid content, porosity and degree of water saturation in the rock. (M. N. Nawawi 2010). It is established that igneous and metamorphic rocks typically have high resistivity values while clay has a significantly lower resistivity than sand. Electrical resistivity is

carried using different electrical configuration (such as wenner and schlumberger) placed at the surface to send current into the ground to measure the generated voltage signal. (Figure 1.3)

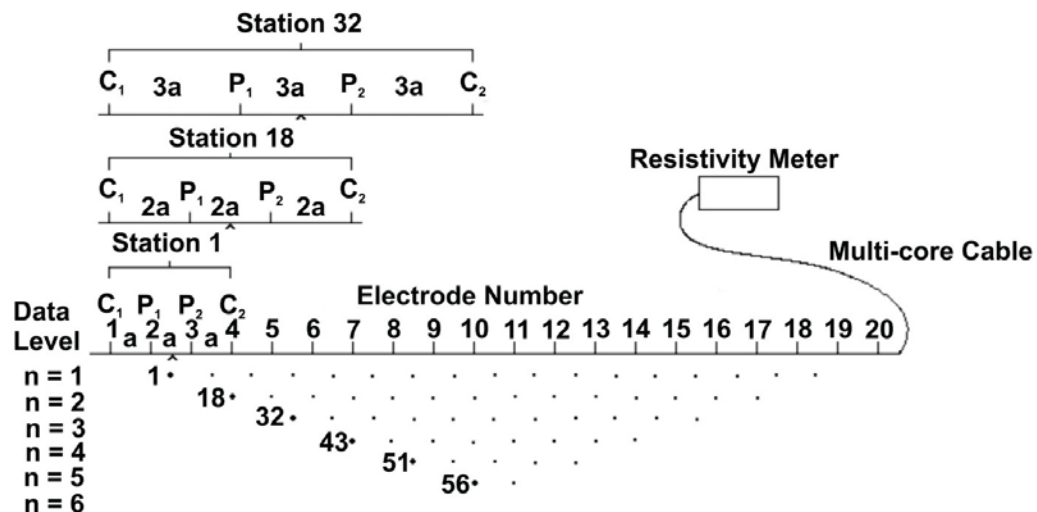


Figure 1.3: Sketch of the electrodes for the 2D electrical resistivity survey and the sequence of measurements for building the pseudo-section [Loke, 2011]

1.2 Seismic Refraction Theory

Seismic refraction procedures principally includes creating waves into the ground through blasts or mallet blows and the subsequent seismic waves are refracted and reflected at interfaces between materials with various densities in the ground, and their movement times are recorded utilizing varieties of geophones. Each seismic ray that strikes a thickness divergence a ratio of the energy is refracted into the underlain layer and the other is reflected.

This strategy utilizes Snell's law to study about the layers underneath the earth surface. From the movement of waves in a medium, various layers and structures underlain the subsurface can be determined.

Fractures can be recognized utilizing seismic strategies that are sensitive to rock mechanical properties and electrical technique that are touchy to rock electrical properties. Electrical technique is especially valuable when the crack porosity is loaded up with a conductive material, for example, water, mud, and mineralization. At shallow depths, seismicrefraction is typically the method of choice since it utilizes the first arrival of seismic energy from explosion to an array of ground geophones. The speed at which the seismic energy travels varies with the density of the subsurface materials making it possible to have profiles of seismic velocity from the variations beneath the geophone array.

1.3 Geotechnical exploration

These studies are majorly aimed at establishing the soil strength that will support the load. The stability of structures is influenced by geotechnical properties of soils, which include density, compaction, permeability, shear strength, particle analysis, and consistency limits. In the study of these properties geotechnical investigation such as test pits and trenches are deployed by directly excavating the ground to obtain samples. The samples are taken to be tested in the laboratory. These methods have been considered to provide reliable information where boring and drilling is difficult though these methods are slow and expensive when exploring to greater depths as they are limited to shallow depths. During excavation the ground is destructed which is likely to alter even the samples extracted. As geotechnical methods prove to be expensive and destructive, geophysical investigation use faster, cheaper and non-destructive techniques to determine subsurface anomalies (Barker, 1993). These methods enhance the reliability and speed by decrease the cost and time spent by geotechnical investigation (Anderson et al., 2008).

Trial pits are done to obtain large bulk samples of soil particularly where visual investigation of the strata is required. This method is of preference compared to drilling because of the relative speed with which it can be carried out. However, this method is not comparable with geophysical methods because of the level of surface disturbance and the difficulty involved in doing effective excavation. This method is carried out when the ground is stable and able to stand unsupported, that is in areas where there is water; excavation becomes problematic due to instability of the walls. Further in obtaining samples in such areas they may not be a true representative sample due washout of fine material. Tranches are extension of test pits where the excavator excavates channels. These trenches provide a continuous exposure of the subsurface material. The disadvantage of this technique is surface destruction of the site during excavation.

Geotechnical boring allows materials to be extracted from the soil either in small or large diameter boring. The materials obtained help in developing the insight of the subsurface topography. However the operation of boring is fundamentally obtaining samples, meaning you cannot obtain data from the boring activity. This therefore implies that the investment in the equipment, labour and time gives a sample that ought to be tested. Further, the soil samples are taken for testing in laboratory where laboratory equipment should be available. The equipment are expensive, require high skilled operator with high maintenance cost. In sample management,

large samples have to be taken from the site and safely availing them in laboratory and wait for results. If the data obtained conflicts and need evaluation, the whole process is done again.

Another major shortcoming of geotechnical boring is that during the boring and extraction process, samples can change the physical characterization. During boring samples loosen and solid soil samples can be less dense than it actually is due to disturbance from their natural state, which consequently affects the grain size of the sample. Boring does not provide the accuracy and efficiency due to getting sample from ground and sending them to the laboratory for testing. The samples are disturbed from their natural state and thereby may not give the exact information on ground.

Drilling is majorly aimed at expanding the knowledge obtained from surface mapping, test pits and trenching at limited depths to provide samples from greater depths and provide access for test equipment for measurement of water level and permeability. The advantage of drilling is restricted to depth of investigation. Drilling has slight effect on environment because the hole can easily be backfilled due to the small size of the hole. Surface disruption is restricted to preparing a drilling pad on a slope ground. The disadvantage of drilling is that the information obtained is indirect either from observation of resistance to bit penetration, measurement in situ properties with equipment being lowered down the hole or by logging of samples recovered by the drilling, a lot of time is taken in drilling and finally it is expensive in maintenance of drilling rigs and require high skilled labor in operation.

In order to describe the geotechnical conditions during site investigation it becomes difficult to access the area with an irregular terrain. Geophysical techniques provide an alternative to evaluating the subsurface formations and thus provide appropriate soil properties (Rucker, 2006). Cone penetration testing (CPT) is a geotechnical in-situ investigation tool where you get data to a depth you want. It reduces time, energy and resources of digging the ground to get samples and taking them to the laboratory for analysis and possibly sealing off the holes made on the ground. CPT provides immediate data thus saving time, expense and risk of handling the samples. The CPT measures the soil properties in natural state with no disturbance making the data to be correct representation of the actual subsurface conditions. However this method has limitations which makes unsuitable especially when investigating in areas with boulder deposits. Further when investigating a wide area for a better presentation more soundings ought to be taken to have a good representation, which is expensive, time consuming and requires high skilled labour.

2.0 Statement of the Problem

Study within the Olkaria Geothermal installations revealed that, the inconsistency in the structural integrity of foundation anchorage could adversely compromise the strength of the structure. Site interpretation for development purposes is extremely vital since it enables designers to adopt prudent safety strategies. Subsurface geological features such faults, fractures, voids and nearness of depth to bedrock are main dangers that are associated to building's establishments in areas that have undergone volcanic activities. This necessitated the need for the study on the proposed site using electrical resistivity methods. This method is of preference compared to geotechnical methods such as boring, pitting, and trenching which are soil disturbing, expensive and time consuming in sample acquiring and laboratory analysis. This geophysical method improve the speed, reliability and minimize the cost of geotechnical investigation.

2.1 Main Objective

To determine the depth to bedrock that forms a firm foundation for development purposes at Olkaria fields using electrical resistivity and seismic methods.

3.0 METHODOLOGY

3.1 Electrical Resistivity tomography

Electrical resistivity is a property that shows how the flow of electric current is opposed in a material. Rock resistivity relies on electrical resistivity of the constituent minerals in the rock, water and air in the pores. Ground electrical resistivity is measured by injecting current into the ground through steel terminals conveyed at specific intervals and another electrode extracts the current. The voltage between the two electrodes that are collinear with the current electrodes is measured. The spacing between the electrodes probes the ground to different depths. Several electrodes are arranged in a straight line with spacing between all electrodes constant. These electrodes are connected to a data-collection instrument that selects four electrodes for a single measurement. The device changes the combination of electrodes so that it measures for all the orderings and spacing.



Figure 3.1: SAS 4000 Terrameter instrument used to collect and record the electrical resistivity data. B, electrodes and cable attachment used for electrical resistivity profiling

Instrumentation

Electrical resistivity data were collected using a Resistivity meter i.e SAS 4000 terrameter system (Figure 3.1). The system is a computer-controlled box connected to electrodes to measure the resulting voltage. This system forms multi-electrode framework (Appendix II) utilizing Electrical Resistivity Tomography (ERT) that ensures all the electrodes transmit the current and detects bad electrode contact in a few minutes. A configuration of Schlumberger– Wenner was used with arrangement of 41 electrodes conveyed along the profile line at an inter-electrode separation differing between 3 m to 10 m interval. This separation is based on the orientation of geographical structures and the intensity of deformation on the ground. The total spread was also varying between 400 m to 800 m depending on the targeted structures and the available space. The acquisition parameters for the eight profiles are summarized in Table 3.1

Table 3.1: Acquisition parameters for the electrical resistivity profiles

Parameters	Value
Electrode spacing (meters)	3.0 (Profile 1)
	10.0 (Profile 2)
	10.0 (Profile 3)
	10.0 (Profile 4)
	10.0 (Profile 5)
	10.0 (Profile 6)

	10.0 (profile 7) 10.0 (profile 8)
Profile length (meters)	800 (Profile 1) 600 (Profile 2) 400 (Profile 3) 600 (Profile 4) 600 (Profile 5) 600 (Profile 6) 600 (profile 7) 600 (profile 8)

The data was recorded through a complex combination of current and potential electrode pairs developing a pseudo cross-section of apparent resistivity underneath the profile. The depth of investigation was dependent on electrode separation and geometry with greater electrode separations resulting to greater resistivity measurements from deeper depths. In electrical resistivity study, depth of investigation is dependent on the relative position of electrodes (Roger Sala, 2007). Eight profiles soundings were done with the traverse acquired in NW-SE direction within the zone of interest (Figure 3.2).

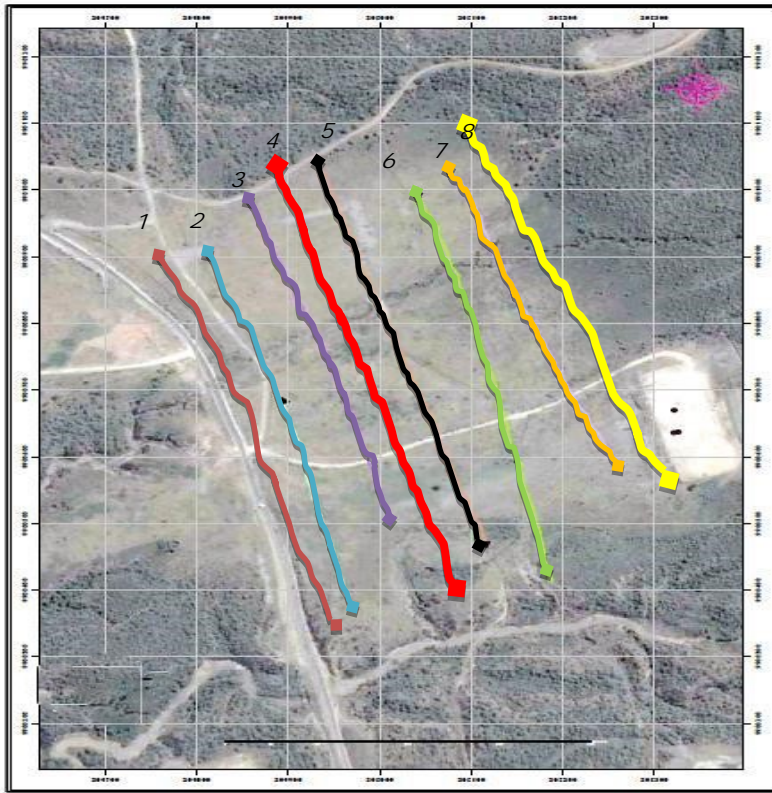


Figure 3.2: Resistivity Profile Lines in the Project Site

Electrical resistivities of different zones on the ground composition were distinguished. The achievement of investigation depended principally on the distinctions in material resistivities, in light of the fact that the more prominent the distinctions, the more exact interpretation results can be interpreted.

Data Processing

The data collected was moved to a PC for purposes of processing. The voltage measurements were used to estimate the electrical resistivity with an inversion utilizing RES2DINV software. The inversion displayed electrical resistivity both lateral and vertical. For the inversion, voltages and currents are combined into a single parameter called “apparent resistivity” (Zohdy and others, 1974); the apparent resistivities calculated from the field measurements and from the model are matched during the inversion by varying the electrical resistivities within the model.

Typical Results

Figure 3.3 shows a representative of the cross section of electrical resistivity of profile 3. The vertical axis indicates the elevation, and the horizontal axis indicates the horizontal distance

along the ground. The cross section represents a vertical slice through the ground, beneath the line of electrodes. The top of the cross section corresponds to the ground surface. The shape of the cross section is trapezoidal. Only this trapezoidal region was thoroughly probed with electrical current; other regions that were partially probed are not shown. The colors in the cross section indicate the estimated electrical resistivity: the red and orange colors indicate high resistivity; the purple and blue colors indicate low resistivity.

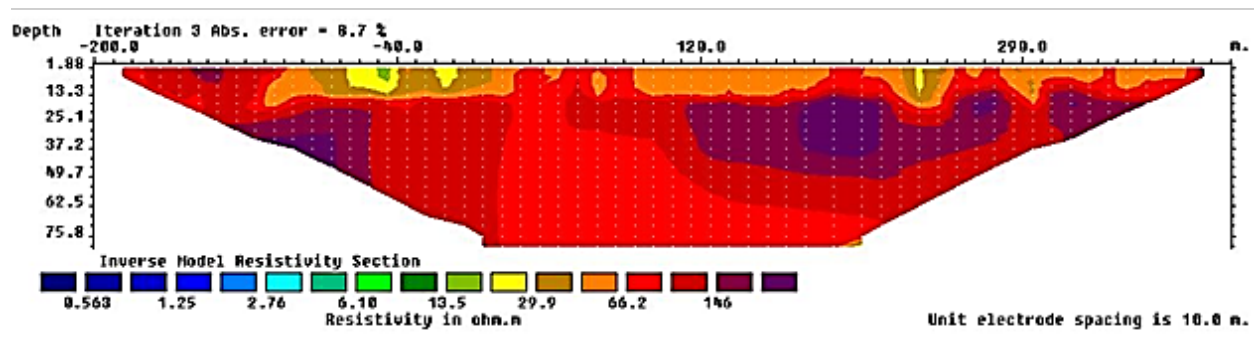


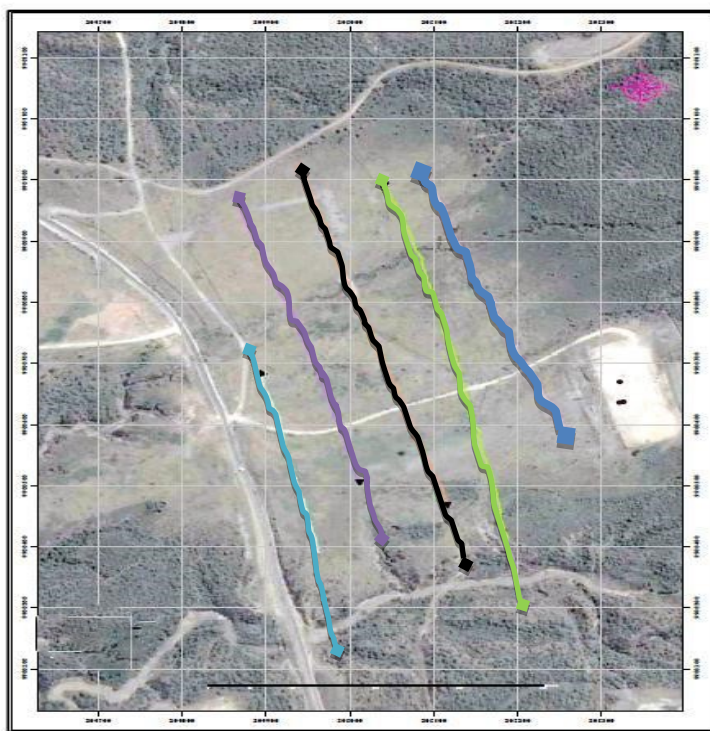
Figure 3.3: Typical results from an electrical resistivity profile (profile 3).

3.2 Seismic Refraction Method

The method uses shear-waves generated on ground to describe geologic heterogeneity in the ground. The Shear-waves are generated on the surface by the source i.e. a metal plates with a small sledgehammer. When the metal plate is hit with the hammer, it generates an impulse force that is transmitted into the ground, generating an *S*-wave. After the *S*-waves are generated by the source, they propagate downward, some is reflected and the other is refracted at interfaces of rock layers then propagate upward. At the surface, the waves are detected by geophones (Figure 3.4) which generates a time varying voltage that is recorded by a Seismograph. The goal of processing the *S*-wave refraction data is to make a seismic cross section that can be related to the geology of the study site. The recorded voltage from each geophone is called a “trace,” and it contains fluctuations in the voltage that correspond to refracted waves, together with other unwanted waves and background noise. Traces from many different locations of the source and the geophones were recorded and this was to enhance the probe at interfaces with the *S*-waves. Using computer algorithms, the unwanted waves and noise were removed leaving the refractions. These refractions were consequently used to generate an image that similar to a geologic cross section.



Figure 3.4: Apparatus used for S-wave seismic refraction profiling. A, Geophone used to detect the S-wave. B, Seismograph used to record the time-varying voltages generated by the geophones.



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Figure 3.5: Seismic Profile Lines in the Project Site

Data Collection

Data was collected along 5 profiles where the acquisition parameters for each profile is shown in Table 3.2. All the five profiles were parallel to the road. The source and geophone were spaced at shorter distance such that the subsurface interface was thoroughly probed. The five profiles ran

50m from each other and trended in the NW-SE direction. Analyses of the seismic cross sections for these five profiles showed how the waves propagated in the ground.

Table 3.2: Acquisition Parameters for the S-Wave Seismic Refraction Profiling.

Parameter	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5
Number of geophones	83	156	153	200	200
Geophone spacing	3	3	3	3	3
Natural frequency of geophones	10	10	10	10	10
Source type	Metal plate	Metal plate	Metal plate	Metal plate	Metal plate
Sledgehammer weight in kg	10	10	10	10	10
Profile length (meters)	250	470	460	600	600

Data Processing

The travel time inversion procedure was conducted for the 2-D analysis using Geometrics SeisImager software (Geometrics, Inc, 2009):

- i. Primary recognition of surface waves
- ii. Creating the dispersion picture board and afterward removing the flag scattering bend
- iii. Back-computing Vs difference with depth (2D inversion)
- iv. Generation of Vs cross-sections from inversion results

The cross-sections were analyzed based on the wave travel to estimate the depth of different strata in the subsurface. This data processing procedure is called and is a type of optimization.

Typical Results

The seismic cross section for profile 1 (Figure 3.6), the vertical axis indicates the elevation, and the horizontal axis indicates the horizontal distance along profile 1. The top of the cross section corresponds to the ground surface, and the other sides indicate the region probed by the S-waves. The cross section has three layers, the top layer has the S-wave velocity less than 160 m/s; the middle layer has the S-wave velocity ranging from 160 to 280 m/s; and finally the bottom layer, S-wave velocity is greater than 300 m/s.

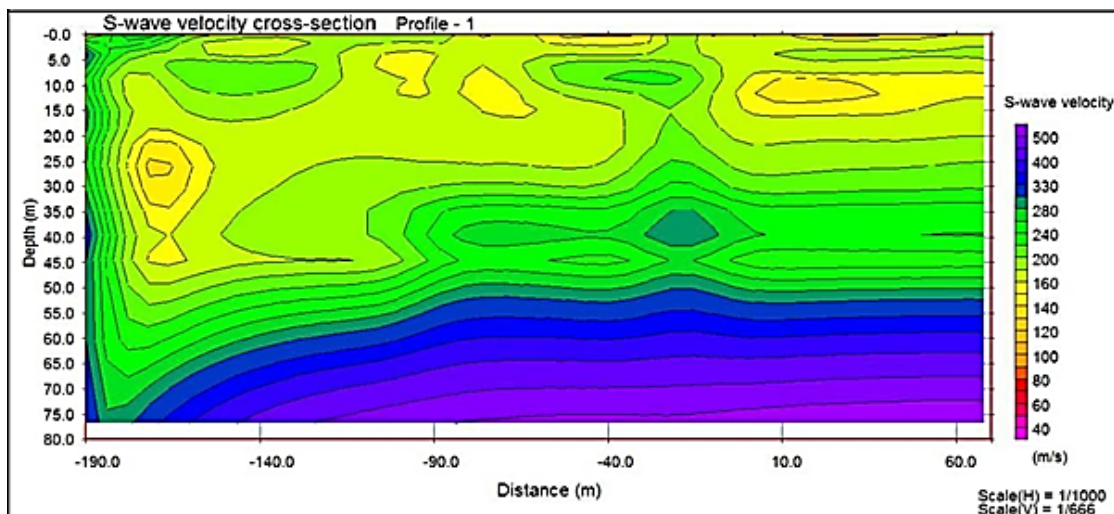


Figure 3.6: Vs Profile 1

4.0 RESULTS AND DISCUSSION

4.1 Electrical Resistivity Results

i. Bedrock mapping

This ERT survey was conducted to assess the bedrock profile prior to power plant construction project and to characterize the soil layers above the bedrock. Inversion models from the acquired data gave reliable information with regard to the ground stability. The qualitative analysis of the profiles is relatively clear from the colour boundaries. The resistivity zones in the profiles are attributed to sediments in layers. Solid bedrock is attributed to the high-resistivity zones ($> 112 \Omega\text{m}$). This ERT survey was able to achieve its main goal, namely to describe the soil below the site, determine the depth to bedrock.

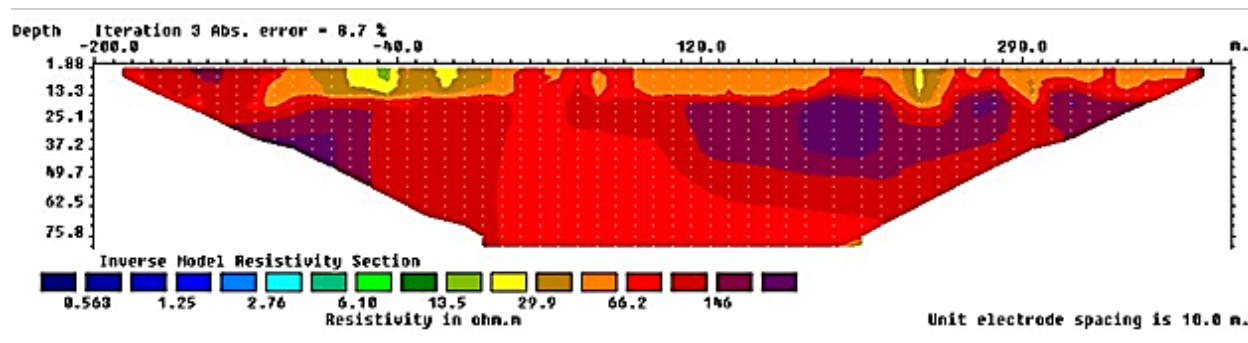


Figure 4.1: ERT profile-3

A very shallow bedrock is observed in the NW part of profile 3 (Figure 4.1) from -100 to -200 with resistivity value of 66 Ωm to about 140 Ωm and this can be seen to extend up to to 75m deep at the central profile zone. It is interpreted as consolidated formation. It forms a very good basement for foundation. Some pockets of high resistivity formations with a resistivity value of above 146 Ωm are also evident at depths below 30m deep below -110m and +200m. This can be interpreted as compact formation and forms a good ground for establishing a foundation.

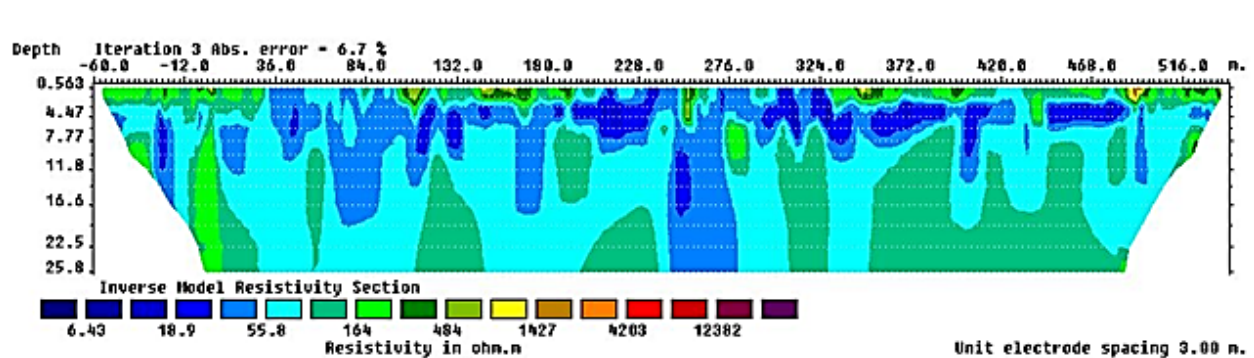
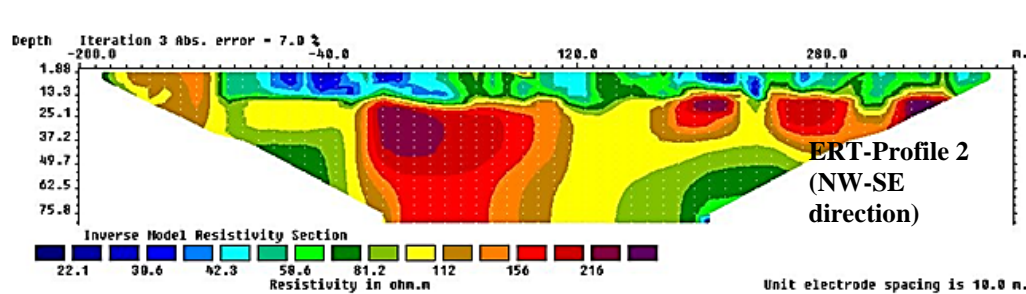


Figure 4.2: ERT profile-1

The ERT profile 1 (Figure 4.2). The resistivity displayed in this profile which is a reflective of subsurface conditions with top superficial layer range from 0 m to about 2 m below ground level and comprising of materials of varying conductivities with resistivity range of 55.8 Ωm to 164 Ωm . This is interpreted to be dry pyroclastic. A very low resistivity ranging from 18.9 Ωm to 55 Ωm is observed below this layer that is irregular in shape on the entire stretch and is characterized by a resistivity which is interpreted as moist pyroclastic with some clays < 18.9 Ωm . This low resistivity of 18.9 Ωm seems to extend deep forming the irregular resistivity structure an indication of the weak points along the profile.



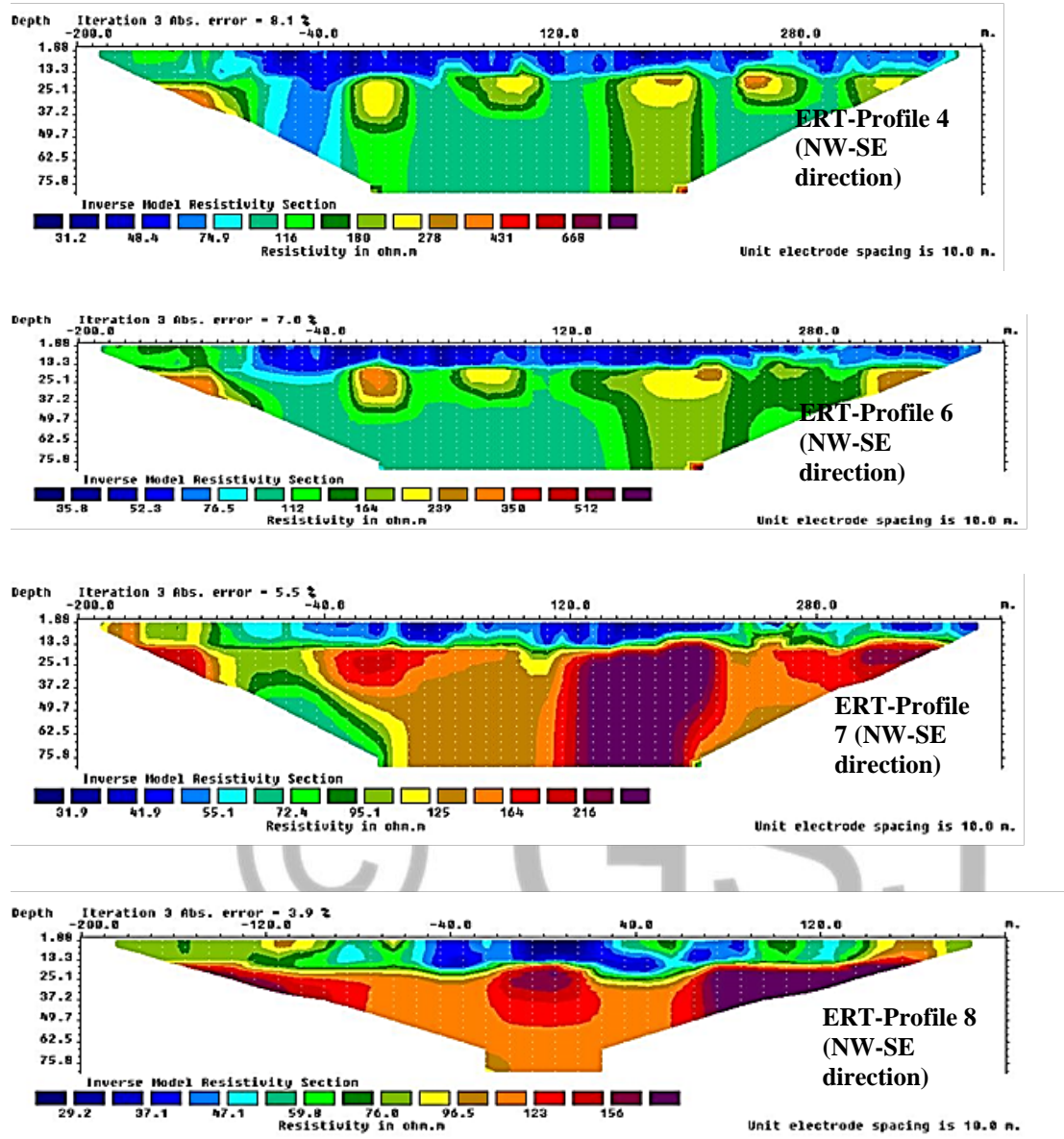


Figure 4.3: ERT profiles 2, 4, 6, 7 and 8

Profile 2, 4, 6, 7 and 8 (Figure 4.3) shows a varying topography with complex resistivity structure due to heterogeneous geology of the area. The top layers consist of very low resistivity penetrating to a depth of about 13m. This layer is interpreted to consist of loose superficial deposits. Below this layer is a bedrock boundary with high resistivity values ($> 112 \Omega\text{m}$) interpreted as stable formation for ground construction. As also noted in the profiles are high resistivity pockets rooted from underneath indicating the presence compact geological formation that is more stable.

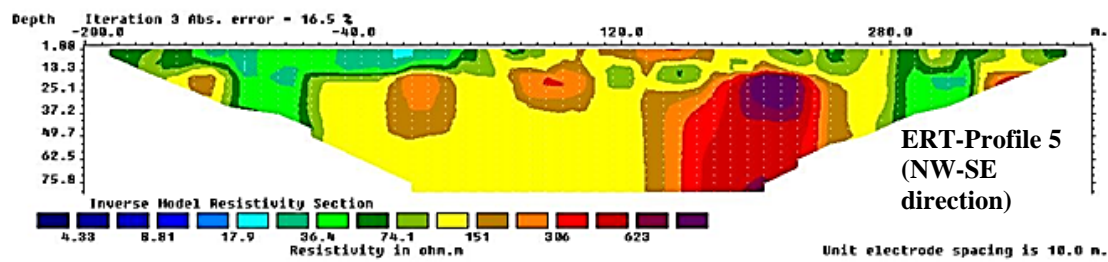


Figure 4.4: ERT Profiles 5

Profile 5 (Figure 4.4) poses a unique resistivity structure that has not been evident in the previous profiles. The near surface resistivity value ranges between 36 Ωm to 306 Ωm. This is composed of loose superficial deposits and some parts are composed of compact formation. Beneath this is a layer with high resistivity value range of between 151 Ωm to 600 Ωm interpreted as composed of stable to very stable formation. The stable formation starts at 3m below ground level and beneath.

The lithology of the Olkaria V field with respect to depth and resistivity based on electrical resistivity can be summarized as in Table 4.1.

Table 4.1: Summary of ERT data interpretation

<i>Profiles</i>	<i>Resistivity</i>	<i>Depth</i>	<i>Probable lithology</i>
1.	18.9-55	2 m	Dry pyroclastic
	164	25 m	Compact material
2.	30-60	13 m	loose superficial deposits
	112-200	75 m	Compact geological formation
3.	29.9-66.2	6 m	Superficial deposits of dry unconsolidated pyroclastic
	66-140	75 m	Compact formation
4.	31-74	13 m	Loose superficial deposits
	116	75 m	Compact formation
5.	36-306	3 m	Loose superficial deposits
	151-600	75 m	Compact formation
6	60	13 m	Loose superficial deposits
	112	75 m	Compact solid rocks
7	40-55	13 m	Loose superficial deposits
	125-216 and above	75 m	Solid rocks
8	35-76	15 m	Loose superficial deposits
	123-156	75 m	Stable ground formation

From Table 4.1, it is evident that the resistivity of the first layer is very low (18.9-76) pointing to a high level of loose material i.e. clay, sands and alluvium. The second layer shows a compact material with very high resistivity values ranging from 76-216 Ohm-m i.e. quartzite, limestone and dolomites.

The ERT results were used to infer the depth of lithological units comprising the top soil (resistivity varying from 18.9-76 Ohm-m and thickness range from 2-13 m); the second layer composed of compact material (resistivity varying from 76-216 Ohm-m and thickness range from 13-75). The high resistivity predicted competent geological material such as limestone and quartz. Very low resistivity suggested clay or sand deposits or water saturated material less competent to support the stability of heavy engineering structures.

In summary, the resistivity displayed in the area under study reflected the subsurface conditions with the top layer dominated with superficial deposits which were composed of unconsolidated pyroclastic. The deposits went to a depth of 13m. Beneath this layer was observed a stable/compact formation. This layer had very high resistivity material which was interpreted to be composed of solid rock materials. This second layer forms the stable formation recommended for structural foundation.

In general, resistivity values were low to a depth of 13m a clear indication that the bedrock is just 13 meters below the surface. The existence of some weak zones along the profiles indicate that the area need excavations before any construction works in the site. These zones of weakness distinguished in the profiles confirmed discontinuous bedrock topography.

4.2 Seismic Refraction Results

Identification of the bedrock and weak zones

This seismic survey was used to characterize the soil stiffness, which was dependent on the wave propagation. The geological features of the subsurface were investigated and the velocity of the wave and depth to the underlying layers were determined. The seismic sections showed three layers from the colour boundaries. The low velocity band had a velocity of 100-160 m/s which is interpreted to be loose soft soil materials as in Profile 1 (Figure 4.5). These materials are weak and have low bearing capacity to be subjected to any load. High velocity band (blue) had a velocity ranging above 220m/s, which is attributed to solid bedrock at depths below 25m. This

band indicates stiff soils which are averagely good for any construction development. The profile runs parallel about 50m offset from the tarmac road and coincided with the ERT survey Profile 1. Both profiles indicated weak and loose materials to depths of 25m drawing a very good correlation between the two cross sections.

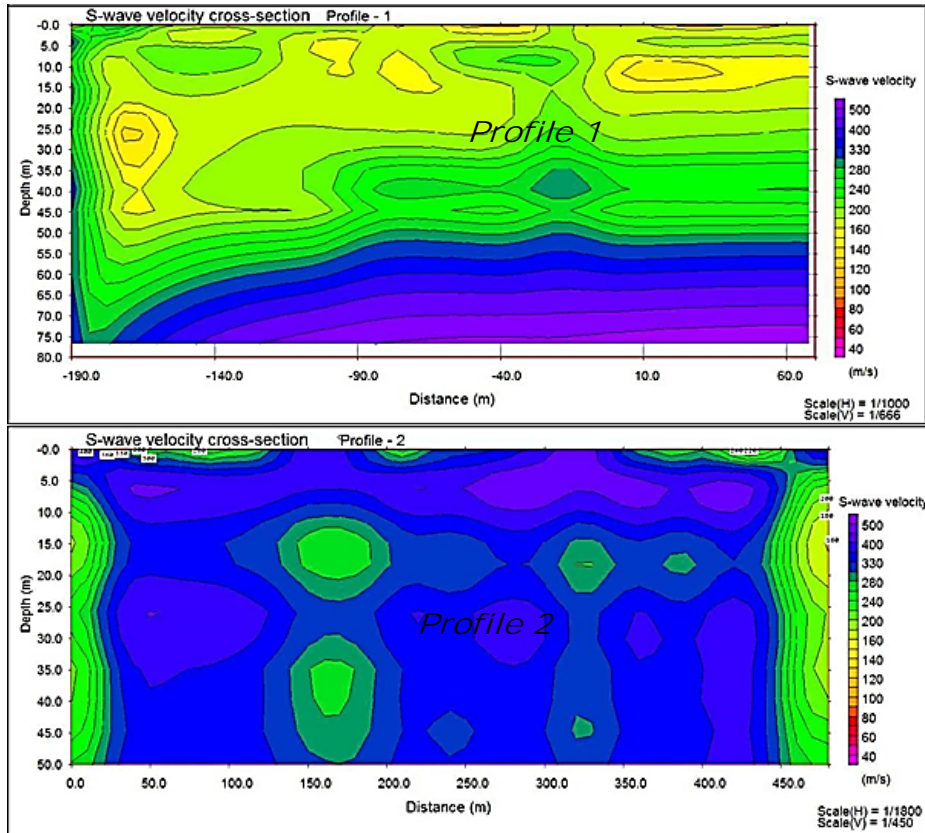


Figure 4.5: Shear wave velocity cross section Profile 1, 2

Very shallow bedrock is observed stretching along Profile 2 extending deep to a depth of 50m. The velocity of wave is high $v_s > 280$ m/s indicating the presence of stiff soils which are competent formation. The V_s profile indicates the area is characterized by stiff soil formation to a depth of 20m. These suitable formations can support load.

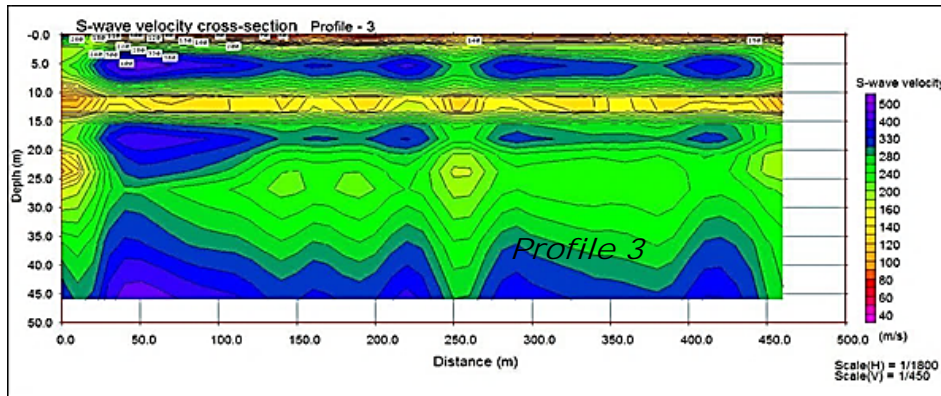


Figure 4.6: Shear wave velocity cross section Profile 3

The seismic Profile 3 (Figure 4.6) indicates the area is characterized by very loose soil formation to a depth of about 2m. This region highly requires site specific evaluation to determine its suitability for engineering foundation. Thin lenses of soft rock and dense formation are also observed at 5m and 20m. At about 250m along the profile, a perpendicular band of $200 <V_s \text{ m/sec} > 240$ is also observed. This may be because of steeply dipping structure cutting through the profile an indication of a weak zone vulnerable to movement. This band is interpreted to be a potential fluid transmission zone that is highly susceptible to relative movements.

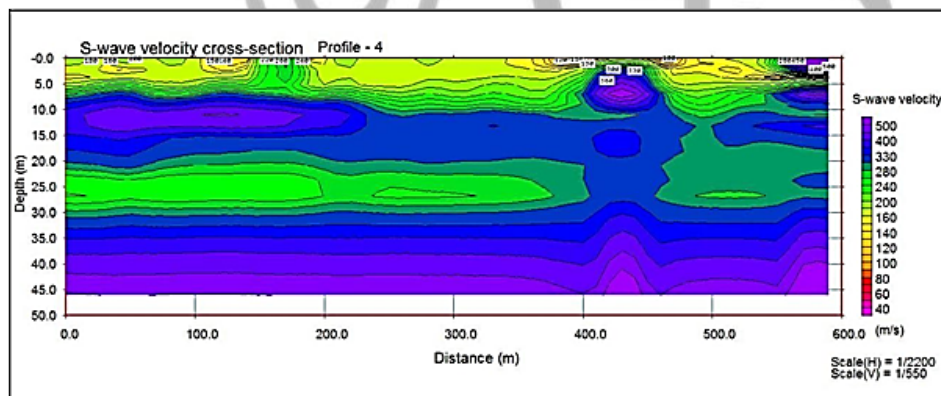


Figure 4.7: Shear wave velocity cross section Profile 4

The seismic Profile 4 (Figure 4.7) indicates an area characterized by loose soft soil formation to a depth of about 5m. A thick bed of soft rock and dense formation is also observed at 5-10m. At about 420m along the profile, a perpendicular band of $330 <V_s \text{ m/sec} > 500$ is also observed. This is assimilated to a rock outcrop almost emerging at the surface. Excavation and backfilling with suitable material to a depth of about 5m is highly recommended to stabilize the ground.

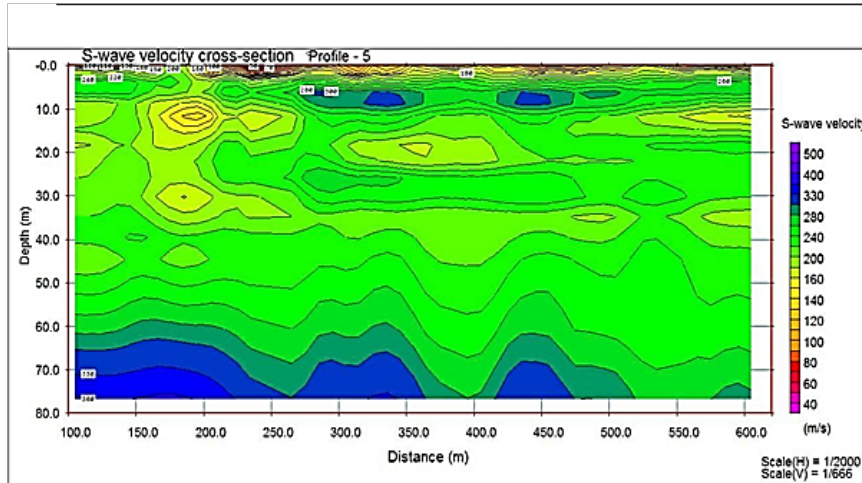


Figure 4.8: Shear wave velocity cross section Profile 5

The seismic Profile 5 (Figure 4.8) indicates the area is characterized by very loose soil formation to a depth of about 2m. Below 2m, the profile soft formation dominates to deeper depths of 60m. This soil formation is not suitable for establishing an engineering foundation.

In summary, shear wave velocity characterized the area with very loose soils to a depth of 2 m and some to a depth of 5m, which had low bearing capacity and required compaction before subjected to any load. Observed also was a perpendicular band which may be a result of dipping cutting structure or a rock outcrop which can be a potential fluid transmission zone that is highly susceptible to relative movement. Thick bed of soft rocks and dense formation was also observed at a depth of 5-10m

5.0 Conclusions

The geophysical studies reveal the structural weakness at shallow depth that is associated to the weak and unconsolidated materials. Compact rock materials were observed from a depth of 14m below ground level. This necessitates mitigation measures such as the utilization of piling such that the proposed infrastructure rest directly on the competent bed. The piles should be anchored to a depth greater than 14m below ground level because the size of the structure to be erected is enormous thus need a stable ground.

The area is characterized by weak Silty material, which has low bearing and consolidation ability. Such materials are prone to frequent washout under conditions of percolating waters hence require utmost care during the placement of engineering structures. In-situ compaction should go before utilization of reinforced concrete amid the development of shallow

foundation to achieve the maximum compaction limits due to the anticipated load of the proposed infrastructure. Further excavation of the top soil and refilling with competent material such as gravel and laterite is crucial to have a strong basement.

5.1 Recommendations

There is need for a more geological study to be carried out and other new geophysical methodologies integrated into this research for vast, quick and competitive results within the Olkaria and its environs. An integrated approach in study of the subsurface conditions should be employed for a wider understanding of soil properties. Similarly, continuous monitoring and evaluation of the site and its environment after the construction of the project should be initiated to establish the ground response towards loading conditions.

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