Application of Shallow Seismic Refraction and 2D Electrical Resistivity Imaging to Site Investigations

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Abstract- A Geophysical study involving 2D electrical resistivity imaging and shallow seismic refraction was conducted to provide support data for engineering site characterization. The case was a potential building site coterminous to the Business School in the precinct of the Kwame Nkrumah University of Science and Technology, (KNUST) Kumasi. The data of interest included depths to bedrock, the thickness and the degree of compaction of the weathered overburden and the variability in the top soil. Collocated resistivity and p-wave velocity data were acquired along fourteen traverses each of length 240 m oriented in the north to south direction. The inter-profile separation was 10 m. CVES resistivity data were collected using the multi-electrode ABEM Terrameter SAS 4000 Lund imaging system in the Wenner configuration with a basic array length of 12 m (minimum electrode spacing of 4 m) and was rolled-along to cover the total profile length. Along the same traverses, the ABEM Terraloc Mk 6, a 24 channel recording system, with a 9 kg energy source and 10 Hz electromagnetic geophones placed 5 m apart were used to collect the p-wave seismic refraction data. The apparent resistivity data were inverted with the RES2DINV software. The soil column (the very near surface) varied in thickness up to 5 m and consists of mostly sandy-clay/lateritic soil with resistivity between 200 Ω.m and 600 Ω.m. Within this layer, there are high resistivity enclaves which are speculated to be loose sand or poorly compacted materials. This resistivity layer is almost coincident with the first of the three acoustic layers identified by the seismic refraction. This zone has average p-wave velocity of 760 m/s. The seismic refraction again delineated a weathered zone which is thicker at the northern section of the site but tapers as it approaches the southern part, extending from 5 to 25 m and 10 to 15 m respectively at the northern and southern parts. The average p-wave velocity is 1300 m/s. The bedrock was delineated depths > 24 m at the north but at shallower depth of about 12 m at the south. The bedrock has p-wave velocity within the range of 3759 m/s to 5321 m/s, with a mean seismic velocity of 4300 m/s. On the resistivity sections, the bedrock was not evident except at the southern part close to the stream.

Index Terms- Site characterizations, Wavefront inversion, KNUST Business School, Acoustic Pseudovolume Structure, electro-stratigraphy and p-wave velocity

I. Introduction

As the building property market booms, and infrastructures age, reports of building failures will continue to ascend. When buildings collapse, people usually advance the arguments of the use poor building materials, construction inadequacies and longevity. Rarely is mention made of the subsurface conditions in terms of the strength, deformation and hydraulic characteristics of the ground which holds the building. Usually, the latter is discussed when buildings are found to be submerging under their own weight. Much attention therefore has to be given to the nature of the subsurface prior to the construction of buildings in the country. Little or no information on the nature of the near surface had led to a lot of buildings constructed on soils with insufficient bearing capability and also with high clay content that potentially can lead to cracks as a result of the anomalous expansion of clay.

Site characterizations or investigations for building purposes are generally achieved through geotechnical investigations. Site investigation is the process of determining the layers of natural soil deposits that will underlie a proposed structure and their physical properties. In the general scheme of things, subsurface exploration and testing involved in site investigations respectively define the following for the soil and rock strata, where applicable. For the soil strata site investigation will seek to reveal its depth, thickness, and variability and relevant engineering properties such as shear strength, compressibility, stiffness, permeability, expansion etc. And for the rock strata, the investigation involves identifying the location of the rockhead and its quality which is determined in terms of the presence of fractures, joint and similar partings (www.dot.ca.gov/hq/esc/techpubs/manual/bridgemanuals, 18th January, 2015).

Geotechnical site investigations are usually intrusive and when **a**ccurately done, form the basis to understanding the potential liabilities associated with any potential construction site. Data obtained during the geotechnical investigations and used to estimate material parameters, such as strength, bearing capacity and unit weight of foundation soils include resistance and frictional characteristics of retained soils, depth to bedrock, and soil stratigraphy.

Site specific information derived from geotechnical site investigations which include such properties as mentioned above could also be obtained through geophysical surveys. Two geophysical methods, namely electrical resistivity and shallow seismic refraction are very popular in site investigations. The electrical resistivity method can be applied to site investigations to characterize the subsurface by locating voids, fissures, faults and also determining the extent of compaction of the weathered zone. The method deployed in the

2D multi-electrode electrical imaging which simultaneously takes into accounts sounding and profiling is most commonly used in geotechnical studies and has successfully been applied to delineate areas with fairly complex geology (Dahlin and Loke, 1998; Griffiths and Barker, 1993; Amidu and Olayinka, 2006; Aizebeokhai et al., 2010; Olayinka and Yaramanci, 1999). Within the precinct of the KNUST, Andrew et al. (2013) were successful in using the electrical resistivity tomography to map and characterize the subsurface at a potential building construction site.

The shallow seismic refraction method is also used in site investigations to determine the depth to bedrock. In recent days, the method has been used successfully to map shear and faulted zones which determine the quality of rock masses. These faulted and shear zones are characterized by an offset in a refraction traveltime curve or low velocity with respect to the host rock. The shear modulus of the subsurface materials can be estimated using the ratio of the longitudinal and transverse sonic velocities obtained from refraction seismic (Sjøgren et al., 1979; Sjögren, 1984).

KNUST has vast land with most parts undeveloped. Over the past decade, the institution has witnessed rapid expansion and there needful to study the near surface characteristics of the potential building sites within the Campus. One such space on Campus is the fallow land between the KNUST Business School and the Gyinase road (Fig. 1).

Location and Geology of study area

KNUST is located on the following longitudes and latitudes respectively with reference to the World Geographic System (WGS) 84 with units in decimal degree; -1.590 and 6.672, -1.564 and 6.678, -1.543 and 6.680, -1.548 and 6.693, -1.564 and 6.662 respectively forming the five corners the KNUST precinct. The study site is located in the KNUST Campus and covers an area approximately 31,200 m^2 (240 m x 130 m).

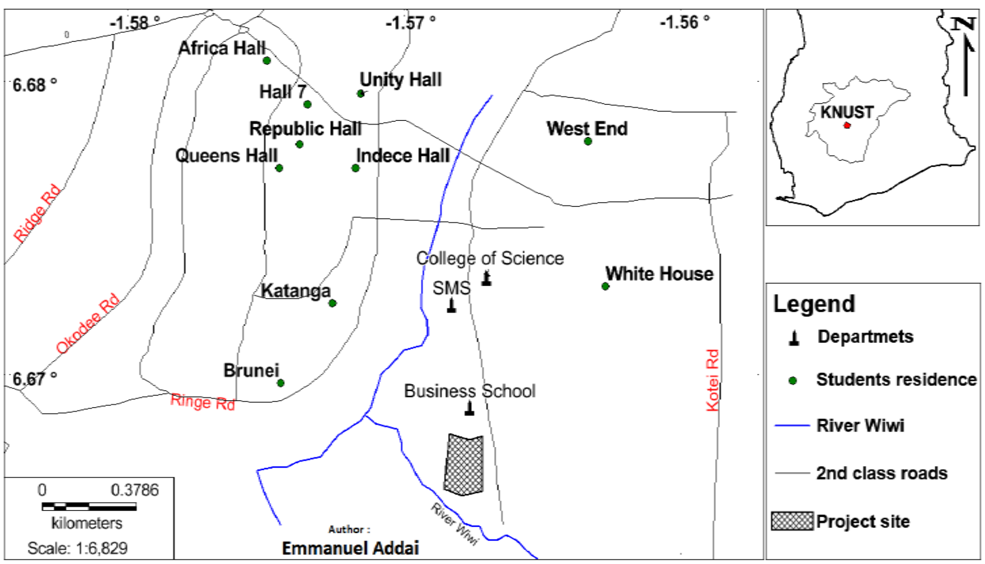

Fig. 1 Location of KNUST showing the surveyed site.

Geologically the Kumasi area is underlain by the lower Birimian system which is composed mainly of schist, phyllites and greywackes intruded by quartz veins and stringers (GSD, 2009). Besides these intrusives is a post-Birimian Precambrian age massive granitic batholiths (Kessie, 1985) cut by pegmatite veins (Fig. 2).

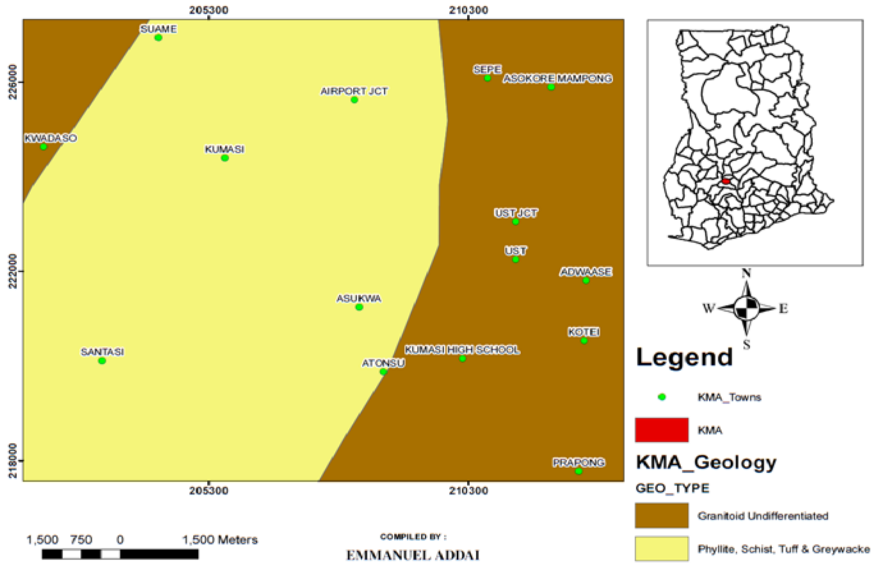

Fig. 2 Geological map of the study area (Modified after Ghana Geological Survey Department, 2009).

II. RESEARCH METHODOLOGY

Geophysical Survey

Layout of geophysical traverses

Fourteen straight profiles, L1 to L14 (Fig. 3), each of length 240 m and trending north-south were created with an inter-profile separation of 10 m.

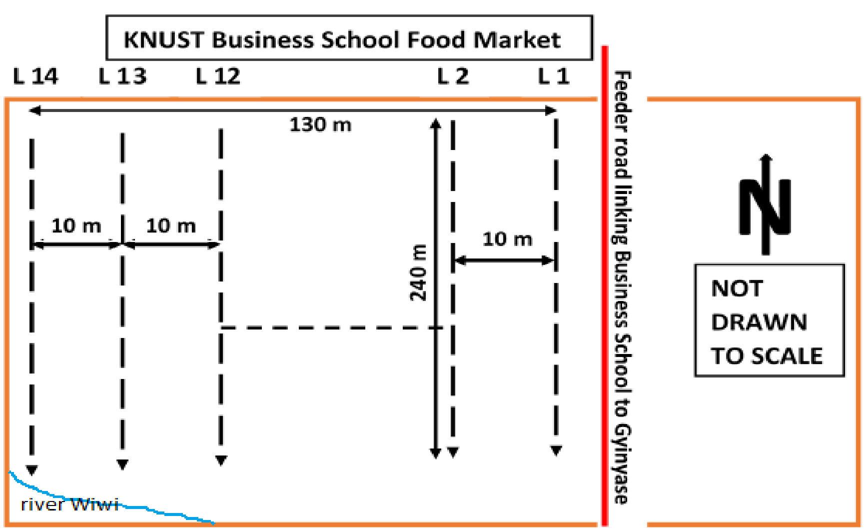

Fig. 3. Sketch of the study area showing location and orientation of profiles along which data were acquired.

2-D resistivity Imaging Survey

In this field work, electrical resistivity data were taken with the ABEM Terrameter imaging device and four multicore cables which have 160 m full stretch. The CVES survey technique was used with sixty one stainless steel (61) electrodes equally spaced at 4 m and arranged in the Wenner configuration, Fig. 4. Current was injected into the ground through two current electrodes and the resulting potential measured with the potential electrodes. The resistivity device (Terrameter) chooses the correct electrode permutations at a time for measurement. The measured potential, injected current and the geometric factor are used to compute the apparent resistivity, Eqn. 1

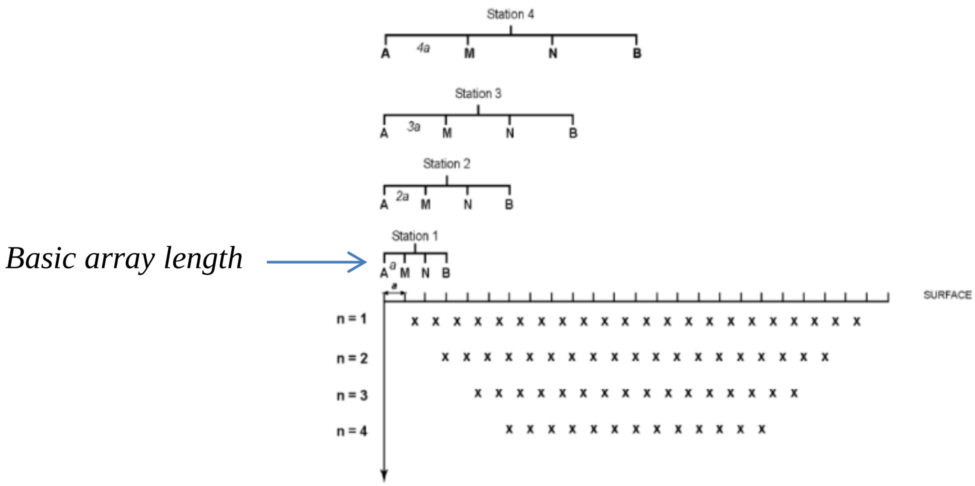

Fig. 4 A Schema of the electrode array in CVES

$$\rho_a = 2\pi a \frac{V}{I} \qquad (1)$$

Shallow Seismic Refraction Survey

Shallow seismic refraction survey was conducted with a 24 channel seismograph, ABEM Terraloc Mk.6, with 10 Hz electromagnetic geophones. Compressional waves were generated with a 16 kg sledgehammer and a metal plate. The geophones were separated by 5 m and each line consisted of two spreads which overlap 30 m. A spread has five shot points (two offsets; the first is 10 m from the first geophone and the second also10 m from the last geophone, two inline shots and one midpoint) giving total of ten shot locations each profile (Fig. 5).

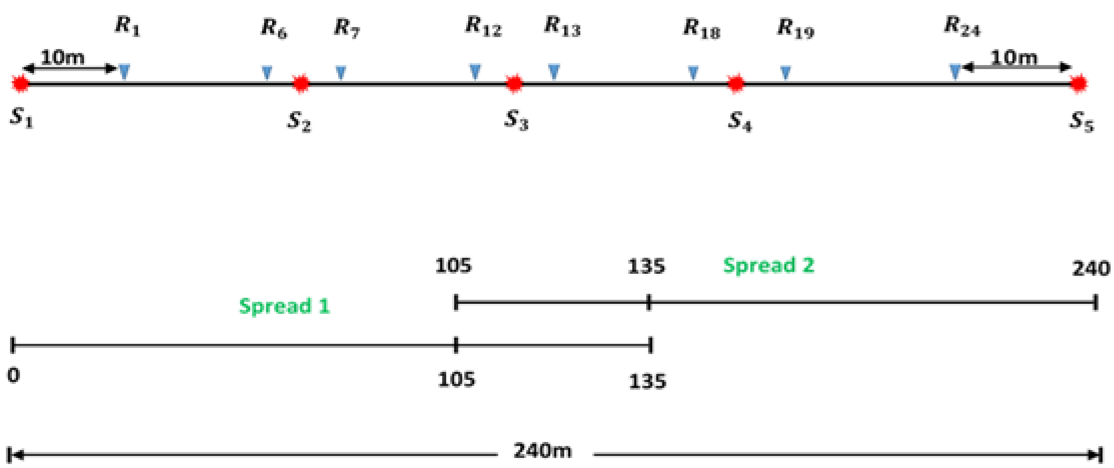

Fig. 5 Geophone locations and shops points along a spread (up) and overlapping spreads (down)

Data Processing and Interpretation

2-D resistivity Imaging

Processing of the ground electrical resistivity field data into a 2D image of the subsurface was done with the RES2DINV software (Loke et al., 2003). The software uses the L_1-norm robust (quite unstable), inversion technique based on regularized least-squares optimization involving finite-element and finite-difference methods (Eqn. 2). It allows sharp resistivity contrast between models.

$$S = \sum_{i=n}^{n} \left| y_i - f(x_i) \right| \qquad (2)$$

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Before the inversion process, the data was first edited. The editing involved incorporating elevation measurements taken with the Garmin GPS to correct for topography and also expunging spiky and negative data points.

Shallow Seismic Refraction

The seismic refraction data was processed with a proprietary software, Reflex W, Version 5 (Sandmeier, 2008). The processing routine of the seismic refraction data involved the following steps:

Seismogram (Fig. 6) is imported and first arrivals are picked (red dashes in Fig. 6).

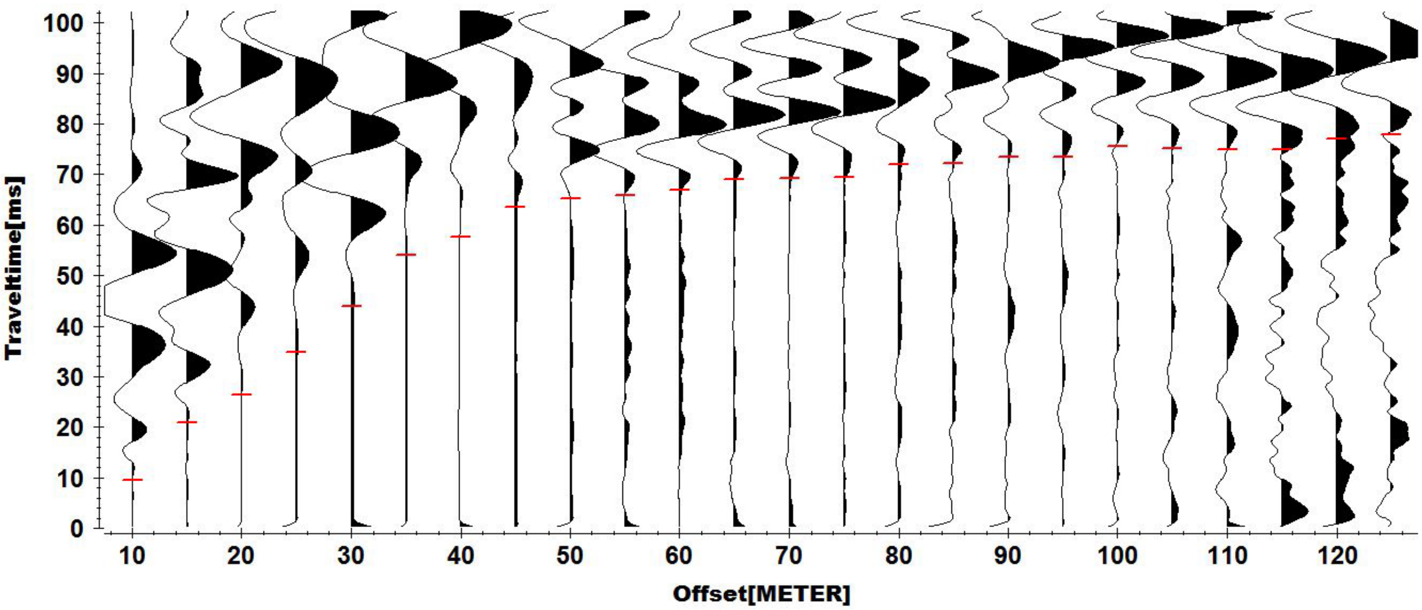


Fig. 6 A seismogram with picked first breaks

All picked travel times are put together and acoustic layers assigned (Fig. 7). The layer reconstruction technique adopted in this work is the wavefront inversion. Limited filtering was applied and no static corrections were effected since the topography at the site was not severe.

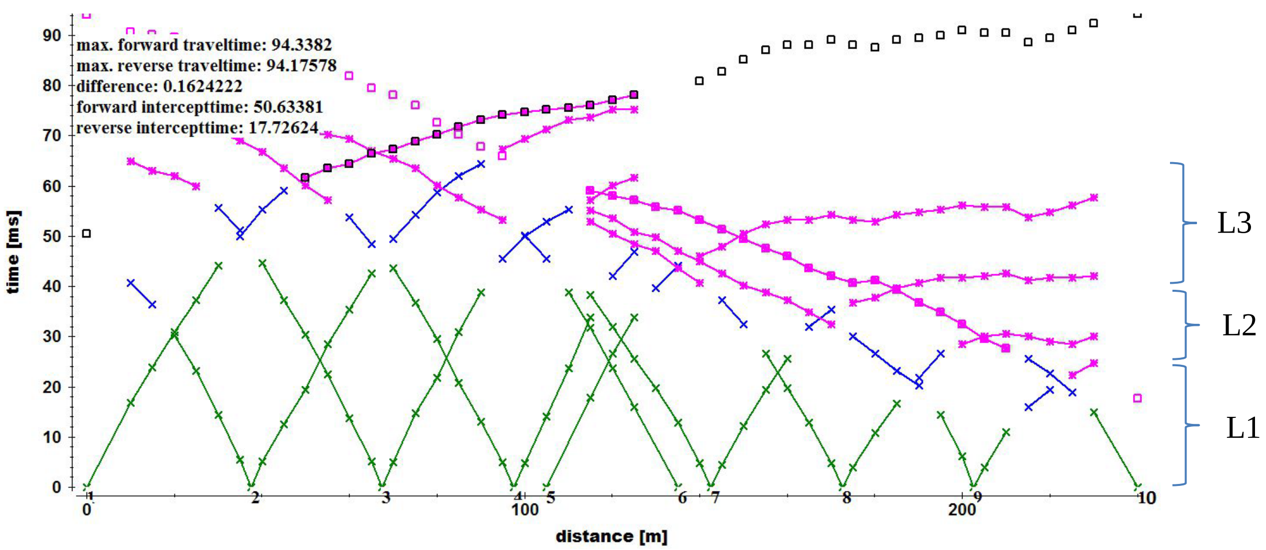


Fig. 7 Combined traveltime curves used for wavefront inversion showing a total forward and reverse traveltimes difference of 0.16 ms.

We used the intercept time method to compute the *p*-wave velocities of the acoustic layers and depths to the refracting interfaces (Fig 8. And Equations (3) and (4). Parallel acoustic interfaces assumed.

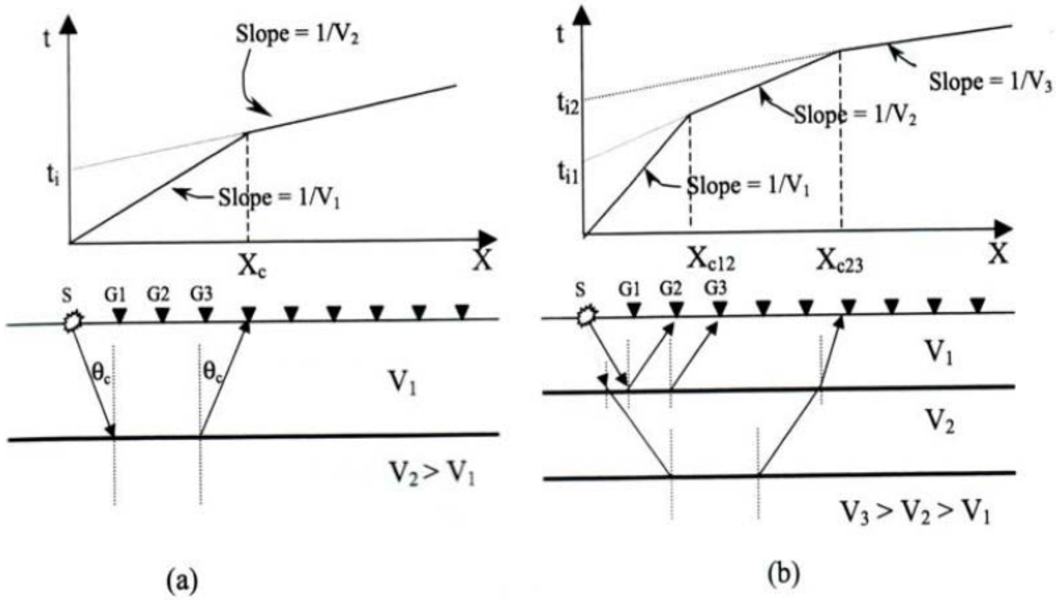


Fig. 8. Ray path and travel time curve (a) two parallel plane layers, (b) three parallel layers (Wattansen, 2001)

$$h_1 = \frac{t_{i2} V_1 V_2}{2\sqrt{V_2^2 - V_1^2}} \qquad (3) \qquad\qquad h_2 = \frac{1}{2}\left[t_{i3} - \frac{2h_1\sqrt{V_3^2 - V_1^2}}{V_3 V_1}\right]\frac{V_3 V_2}{\sqrt{V_3^2 - V_2^2}} \qquad (4)$$

All the traveltime curves of the single shot records for each profile were combined and assigned the various layer velocities to generate 2D models of the underground giving the *p*-wave velocities and thicknesses the identified subsurface structure (Fig. 9).

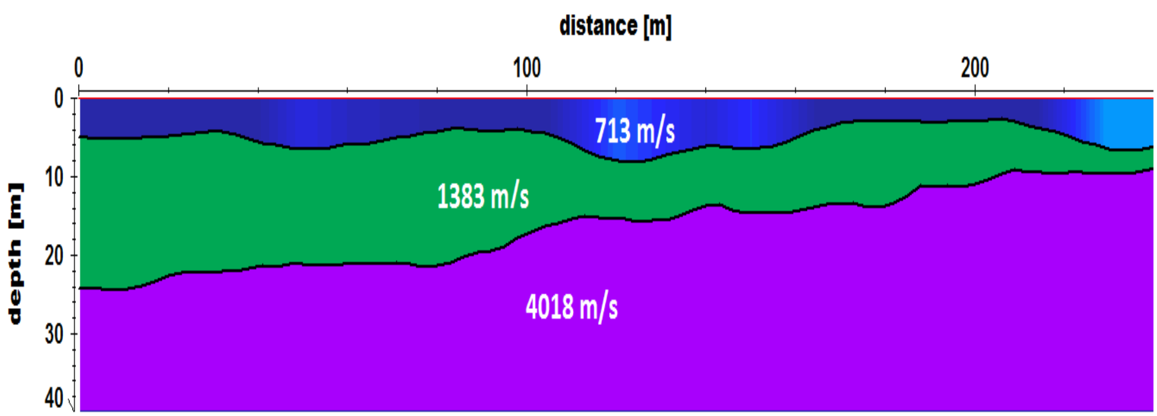
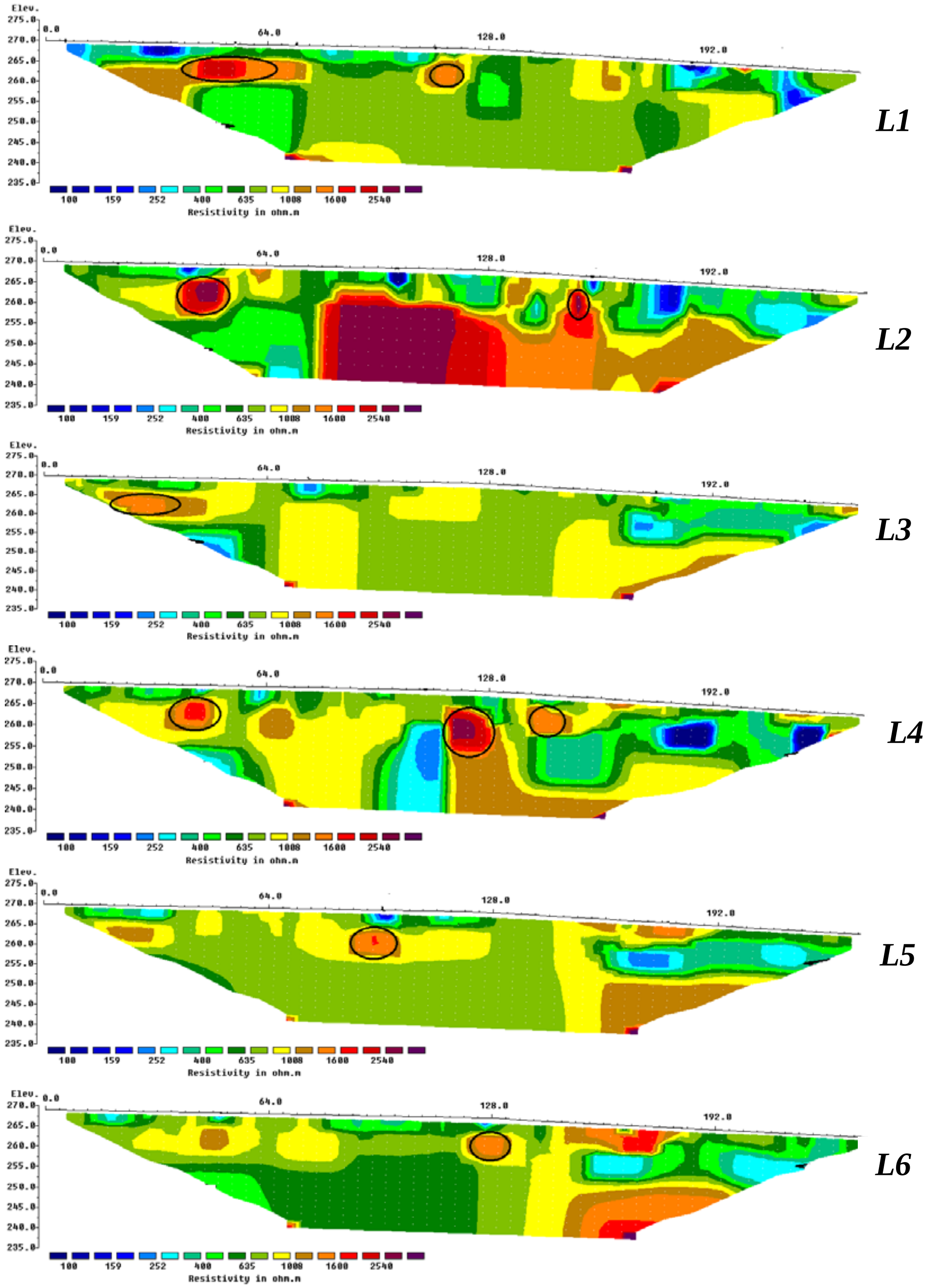


Fig. 9 2D acoustic model of the underground beneath a particular profile; it shows the *p*-wave velocities and corresponding thicknesses

III. RESULTS AND DISCUSSIONS

Results

Apparent resistivity data were inverted to produce 2-D models of the subsurface using an iterative smoothness-constrained least squares inversion. The inverted sections under all the fourteen profiles displaying resistivity for a given traverse as a function of both depth and surface location, are respectively shown in Fig. 10 (*L1 – L14*).



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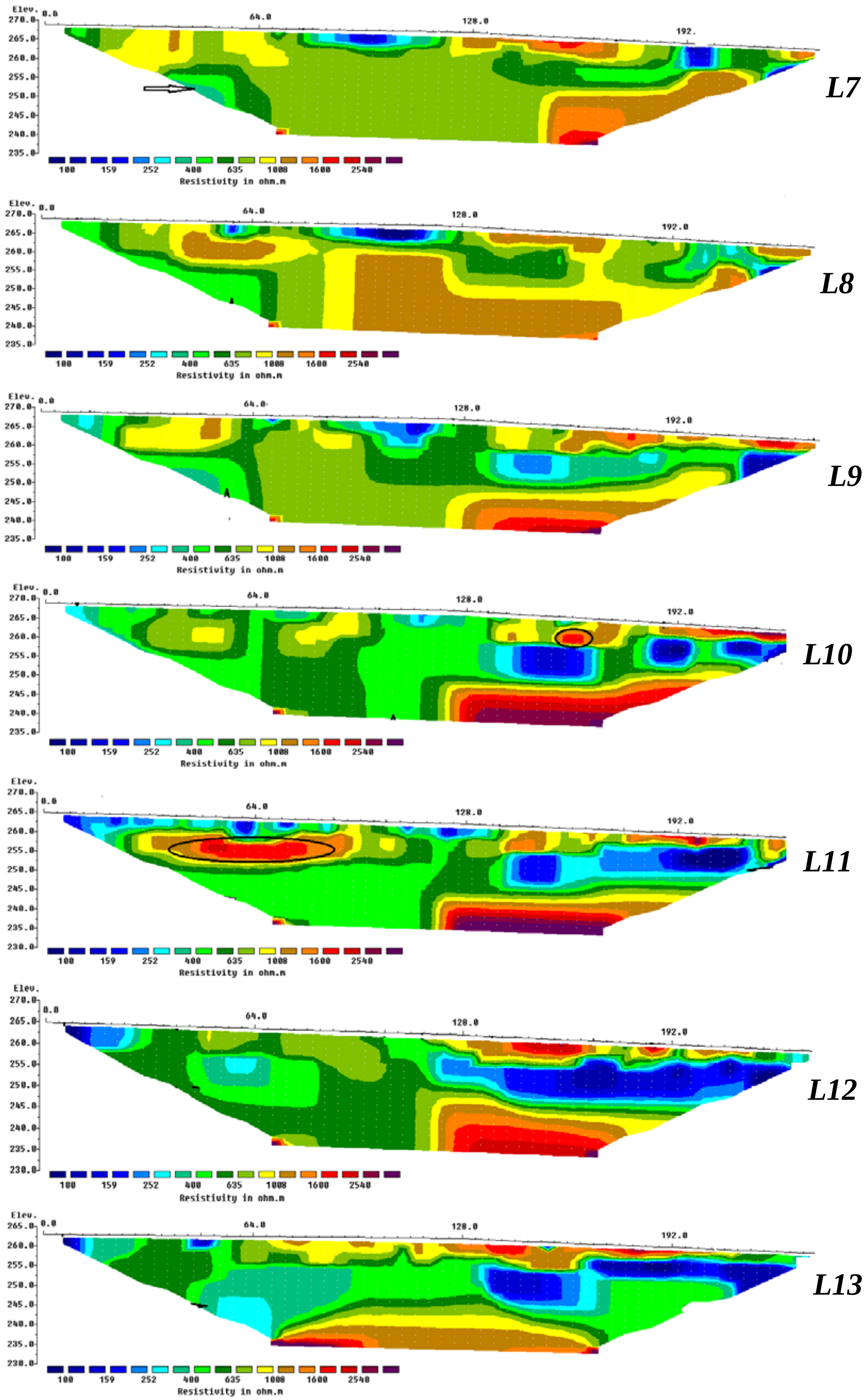

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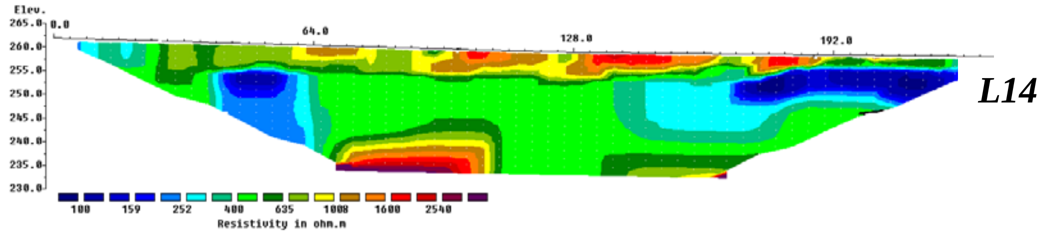

Fig. 10 2-D Resistivity Earth models under profiles 1 to 14 respectively.

The seismic refraction field data for all the fourteen profiles were analysed and interpreted to obtain for each profile location, the seismic velocities for different identified layers. This procedure produced 2-D velocity-depth earth models. These 2-D velocity sections are juxtaposed and presented as acoustic pseudovolume structure of the surveyed site Fig. 11, and a summary of the compressional seismic wave velocities is provided in table 1.

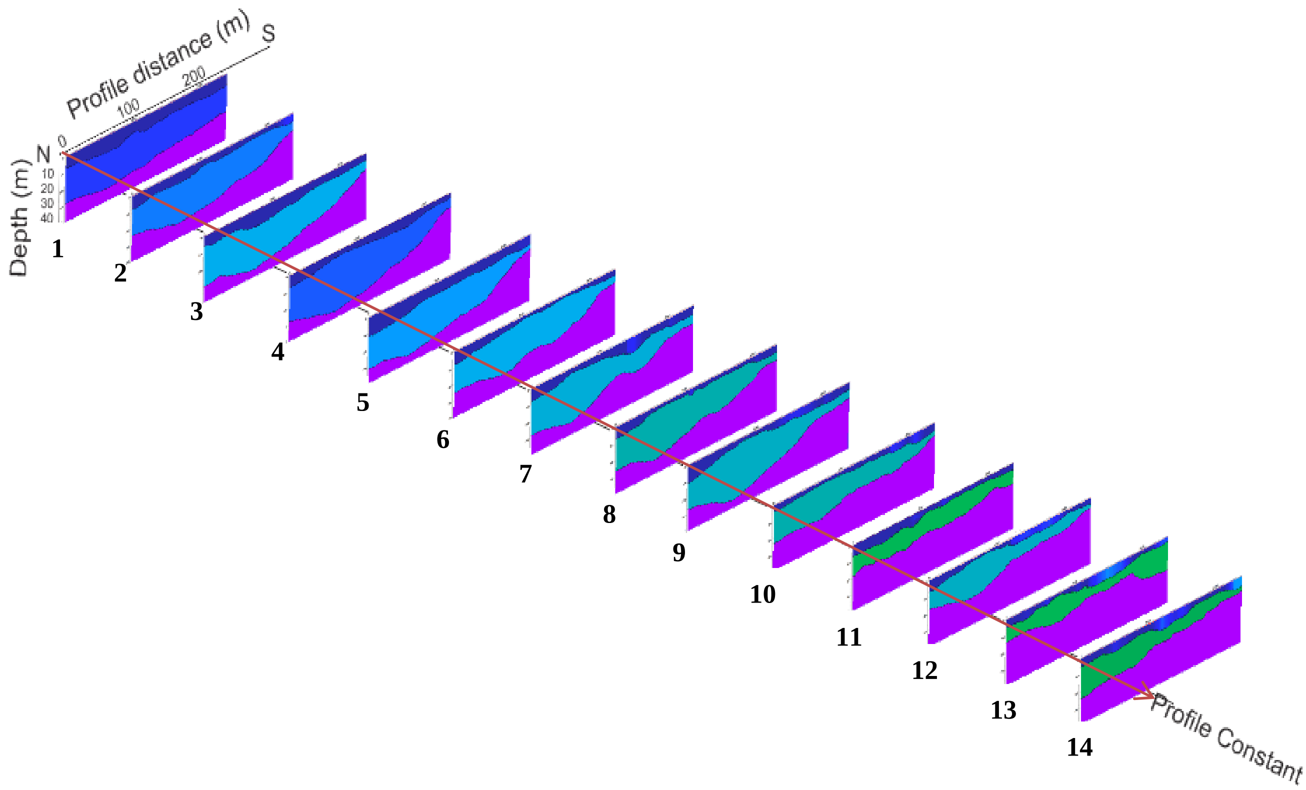

Fig. 11 Acoustic Pseudovolume Structure of the surveyed site. Profile spacing is 10 m. and profile length 240 m

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Table 1. Mean p-wave velocities of the identified layers beneath each profiles in Fig. 11

No.	Layer 1	Layer 2	Layer 3
1	870	1206.7	5321
2	747	1189.1	4817
3	795	1349.5	4678
4	816	1207.3	5016
5	815	1273	4245
6	734	1211.1	3943
7	754	1252.1	4009
8	704	1287	4139
9	805	1379.5	4305
10	699	1211.3	3759
11	712	1433	4063
12	719	1254.4	4012
13	715	1450.5	4192
14	713	1382.5	4018

First layer velocity in the range of 699 to 870 m/s with a mean p-wave velocity of 760 m/s
Second velocity in the range of 1180 to 1450 m/s with a mean p-wave velocity of 1300 m/s
Third layer velocity in the range of 3759 to 5321 m/s with a mean p-wave velocity of 4300 m/s

Discussions

In what follows, the seismic refraction pseudovolume and the resistivity models are discussed to provide an image of the subsurface in terms of (i) lateral and vertical variations in the subsurface geology (ii) degree of consolidation of the very near surface materials (iii) the approximate location of the bedrock surface (iv) the thickness characteristics of overburden.

The electro-stratigraphy of the area Fig. 10 (*L1 – L14*) revealed that up to the depth of about 7 m, from profile 1 to 9 in the subsurface on the east and north show very good compaction and become less compact from line 10 to 14. Resistivity > 1600 Ω.m found in the subsurface to depths of about 3 m close to the end of the profiles at the south is as a result of mixture of loose sand alluvium deposits. The subsurface to 7 m depth for profiles 1 to 9 display moderately high resistivities > 600 Ω.m. Below depths of about 5 m from profiles 10 to 14 the 2D apparent resistivity model sections display dominantly low resistivities < 500 Ω.m which may suggest the presence of highly weathered underground. Confined high resistivity regions (>1500 Ω.m) below depths of about 5 m encountered on lines 1, 2, 4, 5, 10 and 11, suggesting the presence of enclaves of loose soil at those depths.

The results of the seismic refraction survey indicate a subsurface structure that consists of three acoustic layers. The first layer is interpreted to be the top soil/unconsolidated overburden with thickness up to a maximum of 8 m and an average *p*-wave velocity of 760 m/s.

The second layer represents the overburden and it is composed significantly of weathered granite and schist. This layer is variably compacted. This intermediate layer has thickness that varies considerably (between 5 m to 20 m). The average *p*-wave velocity for this layer is 1300 m/s.

The third or the semi-infinite layer is the bedrock. Also shown in the pseudo-volume section (Fig. 11), the bedrock has a down-dip in the Northern part and shows shallow disposition at the southern part close to the stream. The average *p*-wave velocity of this semi-infinite zone is 4300 m/s and the delineated bedrock depth varies between 17 m to 32 m. The bedrock was found at deeper depth of > 24 m at the north with an up-dip in the southern direction about 17 m from the surface which could not be clearly mapped by the resistivity method. The stratigraphic earth model revealed by the shallow seismic refraction survey is shown in Fig. 12.

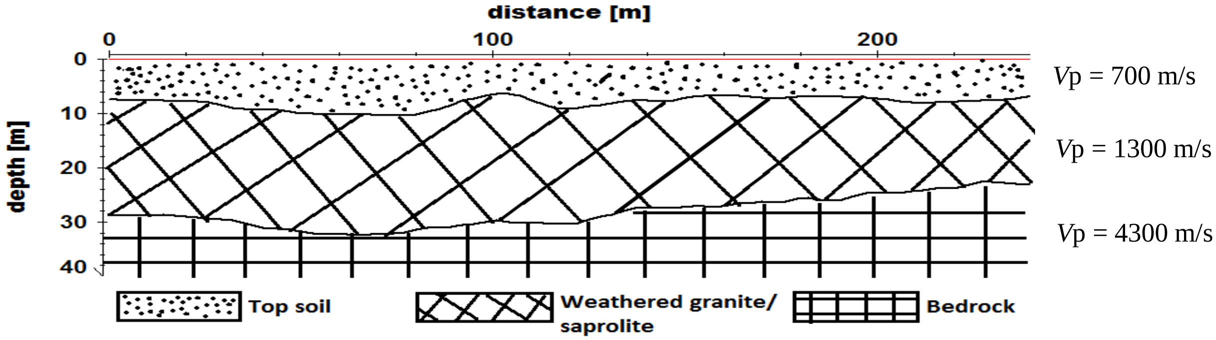

Fig. 12 The stratigraphic earth model revealed by the shallow seismic refraction survey.

IV. CONCLUSION

Interpretation of the resistivity and the seismic refraction data have been successfully been used to determine the thickness of residual soil layer and depth of bedrock in the study area. Generally, the subsurface show a very compact weathered zone at the North and East. The South and part of the West have weak and highly weathered zone, a signature of an incompetent subsurface with very low bearing capacity. The bedrock has a down dip in the South-North direction very shallow in the subsurface about > 12 m at the South and > 23 at the North. Thus the bedrock is very eminent close to the river.

Generally, the subsurface is made of clay, sandy-clay, fairly weathered granite and schist, laterite, dry loose sand. Again within the very near surface of the study site, no structures were found which are considered inimical to the foundations of future engineering structures. This study has showed the significance of combination of geophysical tools in engineering site investigations.

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