Integrating Geotechnical and Geophysical Methods in subsurface characterization of phyllitic-schist profile

N.K. Ayeh[1],
PhD. Student, Civil Eng. Dept., KNUST, Kumasi

S.I.K. Ampadu[2], F. J. Ayeh[3], F. Owusu Nimo[4], F. Charkley[5]
Civil Eng. Dept., KNUST, Kumasi

ABSTRACT: An integrated approach of geotechnical investigation and geophysical survey was used to characterize a lateritic subsurface profile over phyllitic schist . The study site was delineated into three study areas based on the local topography. Borehole drilling with standard penetration test (SPT) was conducted in the three study areas with associated laboratory tests on recovered samples. The geophysical properties of the subsurface was determined from electrical resistivity tomography (ERT) along profile lines and vertical electrical sounding (VES) conducted at the location of the boreholes. Borehole data was interpolated to obtain subsurface description of the site. The role of parent rock type and topography and drainage conditions has a major influence in the texture of soils developed in a tropical environment. The findings of the geophysical survey indicate a heterogenous subsurface which is not captured in the subsurface profile generated from borehole data only. The study shows that an integrated approach should be adopted to give a detailed characterisation of a subsurface profile developed over phyllitic schist for civil engineering purposes.

1 INTRODUCTION

In Ghana, the most common method of geotechnical site investigation for foundation design of civil engineering infrastructure is by borehole drilling with its associated laboratory testing. Even though in this method the data is obtained at isolated locations, it is nonetheless used to generate generalized subsurface models. The accuracy of the subsurface model can be improved by using a larger number of boreholes, but this increases the cost of the investigation. Geotechnical engineers are faced with the challenge of finding a balance between cost and safety. This calls for the need to adopt an integrated approach that gives a detailed and accurate characterisation of the subsurface and yet is cost-effective. Geophysical surveys have become a promising approach to complement geotechnical site investigation over the years. Geophysical methods are based on the measurement of specific physical properties of subsurface soil such as their resistivity to electrical current flow. They are non-invasive and involve affordable instrumentation making it inexpensive to conduct. Moreover, a well-distributed information of the subsurface that may otherwise not be discovered by a realistic drilling program can be reconstructed. Geotechnical and geophysical methods when properly integrated in a site investigation program, limit ambiguity in the interpretation of the subsurface characteristics driven by large amount of heterogeneity in soils. Integration of geotechnical and geophysical survey has been used extensively in the characterization of subsurface profile and identifying anomalies that affect construction (Sudha et al, 2009; Aizebeokhai et al. 2010).

Due to the high rainfall and high temperatures in the tropics, the predominant soils are laterite and lateritic soils and most site investigation programs take place in these soils. Lateritic soils are known to have higher proportions of the oxides of iron and aluminium (sesquioxides) and may be identified by their low silica: sesquioxide ratio (SSR). The objective of this study is to demonstrate how supplementing traditional geotechnical investigation methods with geophysical surveys can provide a detailed subsurface description of a laterite and lateritic soil formed over phyllitic schist.

2 METHODOLOGY

2.1 *Selection, description and delineation of study site*

The study site was selected based on the known influence of topography on weathering (Ampadu 2016). The study site is located on KNUST campus within the Kumasi District in Ghana and it covers an area 0.22 km^2. The local topography initially slopes steeply with an average gradient of 4 % and then gently into a valley. For purposes of the investigation, the site was delineated into three areas designated as the upper slopes (H), middle slopes (M) and valley (L) based on the local topography. Geotechnical and geophysical surveys were conducted at each area. Figure 1 shows the location of the site including the investigation points.

Figure 1 GPS Location of site and investigation points

2.2 *Geotechnical Investigation*

2.2.1 *Fieldwork*

One borehole was drilled at the center of each area as shown in Figure 1 (BH1 at upper slope, BH2 at middle slope and BH3 at valley) using the Dando 2500 cable percussion rig to a maximum depth of 10.0 m. During drilling, small disturbed soil samples were taken and visually logged. The recovered samples were collected into plastic bags and labelled appropriately for laboratory testing. The Standard Penetrating Testing (SPT) was also conducted at 1m intervals in each bore-hole. Figure 2(a) shows the SPT in progress. The result of the SPT test is expressed by a resistance index to dynamic penetration, N_{SPT}.

2.2.2 *Laboratory work*

The laboratory work consisted of the index properties of the samples retrieved from the boreholes. The disturbed soil samples recovered were air-dried for at least 7 days. The index properties were determined according to specifications described in the British Standards, BS 1377: 1990, Parts 1 and 2. The particle size distribution was evaluated by using hydrometer and wet sieving meth-ods. Sodium hexametaphosphate (IV) was used as a dispersant solution in the hydrometer method. The Atterberg limits test was conducted on samples after sieving through the 0.425 mm BS sieve. The liquid limit was determined using the cone penetrometer method and the plastic limit was performed by the rolling thread method.

2.3 *Geophysical Investigation*

2.3.1 *Electrical resistivity Tomography (ERT)*

The electrical resistivity tomography (ERT) technique which provides 2D images of the subsur-face at various points along profile lines was used. The equipment consisted of a multi-electrode system, ABEM Terrameter LS manufactured by ABEM Corporation (Fig 2b). ERT was conducted along profile lines H2-1 to H2-2, M2-1 to M2-2 and L2-1 to L2-2 (Fig 1). The maximum length of the profile line was 160m with a maximum electrode spacing of 2.0 m, in order to increase the image resolution of the subsurface for better comparison with the geotechnical results. The dipole-dipole array was selected for acquisition of data at ERT sections since previous studies by Neyamadpour et al. (2010) has shown that the dipole-dipole array gives a better resolution for shallow depths than some of the commonly used ERT arrays. Raw data from field measurement was processed and analyzed using the RES2Dinv software developed by Loke and Baker (1996). The software allows pseudo-sections of apparent resistivity to be converted to a subsurface electrical resistivity distribution to provide a 2D inverse model that approximate the actual ERT profile of the subsurface. The quality of each ERT profile was analyzed by the RMS (Root Mean Square) error between the measured and calculated model.

2.3.2 *Vertical electrical sounding (VES)*

A vertical electrical sounding (VES) station was positioned at the vicinity of each borehole to determine the variation of electrical resistivity with depth. Electrical data was acquired using mini-res resistivity meter from L and R instruments INC., and stainless-steel electrodes (Fig 2c). Electrical resistivity sounding was conducted using the Schlumberger electrode configuration with electrode spread to a maximum of 20 m corresponding to an investigation depth of about 10 m. During the investigation, electrical current was injected into the soil and the resistance offered was computed in real time. The 1D apparent electrical resistivity was determined as the product of the geometric factor of the array used and the electrical resistance values.

(a) (b) (c)

Figure 2 (a) SPT during Percussion drilling (b) Electrical Resistivity Tomography survey and (c) Vertical Electrical Sounding test

3 DISCUSSION OF RESULTS

3.1 *Geotechnical subsurface characterisation*

The site lies within the moist semi-deciduous forest zone of the country. The distribution of rainfall and temperature in a typical year are bimodal and characterised by wet and dry seasons; the major raining season being June with an average rainfall of 214.3mm and a minor season in September with an average rainfall of 165.2mm Geologically, the site is underlain by parent rocks belonging to the Lower Birimian formation system comprising metamorphosed sediments of Precambrian origin predominantly phyllitic schists and phyllites intruded by granites. The overburden soil is the weathered products of this parent rock.

Figure 3 is a topographical cross section through the study site showing the boreholes interpreted to a maximum depth of 10.0 m prepared by interpolation from borehole data.

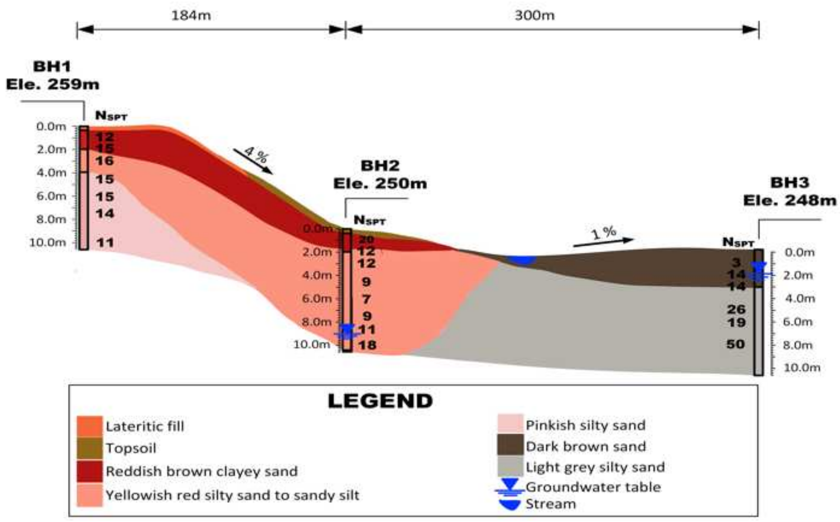
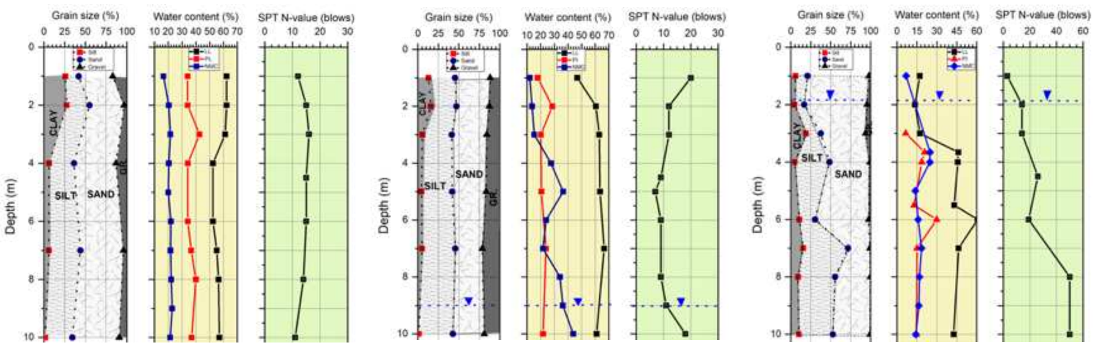


Figure 3 Topographical cross section through subsurface profile of study site

The variation of the geotechnical parameters (grain size distribution, natural moisture content (NMC), liquid limit (LL); Plasticity Index (PI) as well as the SPT N-value (N_{SPT}) with depth at each borehole location is shown in Figure 4 (a) (b) and (c). Figure 4(a) shows the profile in BH1 which is assumed to represent the upper slope. It is predominantly high plasticity clayey sand with a clay content of about 25% at the top 2m which reduces with increasing depth to become silty sand. The gravel content appears to compensate for the reduction in the clay content.



(a) (b) (c)

Figure 4 Geotechnical profiles at (a) upper slope (b) middle slope (c) valley

The profile in BH2 shown in Fig 4(b) representing the middle slope is similar to that of the upper slope but with higher gravel content (15 % to 20 %). Figure 4(c) shows that in BH3, representing the valley, up to a depth of 3.0 m, more than 50 % of the total percentage of the soil is non-plastic sand. Below 3.0 m, the samples tested behave as silts of intermediate plasticity. Previous studies conducted on lateritic soils have shown that phyllite and gneiss soils are clayey or silty (Frempong, 1994). Gidigasu (1976) in a similar study attributes the high sand content to the concentration of dissolved silica in the valley remaining in the residual wash carried from the upper slope. The chemical analysis carried out on samples from the three boreholes showed that apart from the top 2m in BH1 which is a true laterite according to the criteria by Morin and Tudor (1975), the rest of the material in BH1 and BH2 constitute a lateritic soil. In BH3 the SSR values reduces from 14 at the top to an average of about 2.1 from a depth of 3m implying that the material in the valley is non-lateritic. This highlights the role of topography as a major soil-forming factor in the tropics.

The strength profile represented by the N_{SPT} show the values in BH1 the values increasing from 12 at the top to 17 at 3.0m and reducing to 11. In BH2 it reduces from 20 at 1m depth to a minimum of 8 at a depth of 6m and increases to 17 at 10m. In BH3, however, N_{SPT} increases from 3 at 1m to refusal at the depth of 8m. It is observed that despite the high ground water level of 1.8m in BH3, the N_{SPT} continued to increase with depth, indicating that at low clay contents, groundwater does not appear to influence the N_{SPT} values.

3.2 *Geophysical characterization of subsurface*

The results of the VES at the borehole locations are shown alongside the ERT survey results in Figures 5 to 7. The 2D resistivity models developed from the ERT survey were generated after the 7th iteration and the root mean square (RMS) error was between 8.3 % and 13.8 %. The 2D resistivity-depth models depict a heterogenous geo-electrical subsurface. Figure 5 shows the VES resistivity model at the upper slope. The VES shows resistivity increasing from about 300 Ωm at a depth of 1m to about 850 Ωm at the depth of 10m. However, the different ERS models to the left and to the right of BH1 is striking. To the left of BH1, the resistivity is high and more uniform of the order of 1300Ωm. To the right, however, within the first 30m of the borehole, the resistivity is low ranging from about 40Ωm to 550Ωm and thereafter it becomes more heterogeneous with pockets of very high resistivity within the top 4m depth and very low resistivity from the depth of 5m. The ERT results shows that the extrapolation made for the subsurface model from the BH1 and BH2 is an oversimplification. Also, the extrapolation of the results of VES at one location of BH1 is also an oversimplification. The implications of the different geoelectric zones for the soil's engineering properties, however, is not clear.

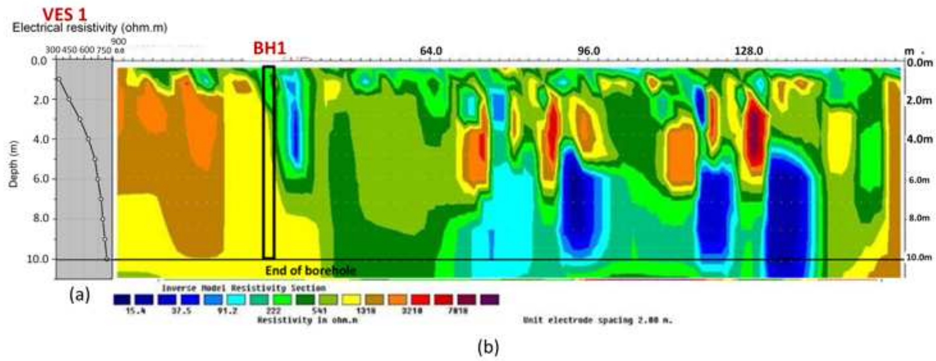


Figure 5 (a) VES and (b) Electrical resistivity model along profile line at the upper slope

For the middle slope, the VES in Figure 6(a) shows only a fairly constant resistivity profile with values varying between 700 Ωm near the top to about 750 Ωm at a depth of 10m. For the ERT in Figure 6(b) again the profile immediately to the left of BH2 has more uniform resistivity values ranging from 560-1100Ωm over the depth of 10m which is different from that immediately to the right of BH2. For the first 30m to the right of BH2, the resistivity is more heterogeneous with pockets of values ranging from less than 300Ωm mostly within the top 4m and high resistivity values as high as 9154 Ωm. The geotechnical profile obtained by interpolation of the borehole logs of BH1 and BH2 does now capture this heterogeneity in the resistivity values.

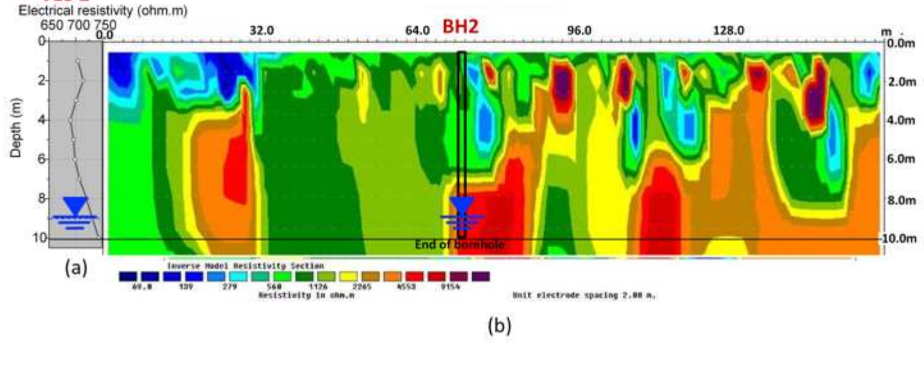


Figure 6 (a) VES and (b) Electrical resistivity model along profile line at the middle slope

Within the valley, the VES in Figure 7(a) shows low resistivity values increasing from about 224Ωm at the top attaining a maximum of 274Ωm at the ground water level and reducing 78Ωm at the depth of 10m. For the ERS, a first geo-electrical layer up to a depth of about 3.0m is of low to intermediate resistivity with values ranging from 40 Ωm to 300 Ωm. Below this the second geo-electrical layer is an intermediate to high resistivity zone (211 Ωm to 700 Ωm). Due to the low resistivity of water, it is expected that the resistivity of a saturated soil will be lower than the unsaturated condition. The data clearly confirms the decrease in electrical resistivity value after encountering groundwater. However, the heterogeneity is not predicted from the geotechnical profile shown in Figure 4(c).

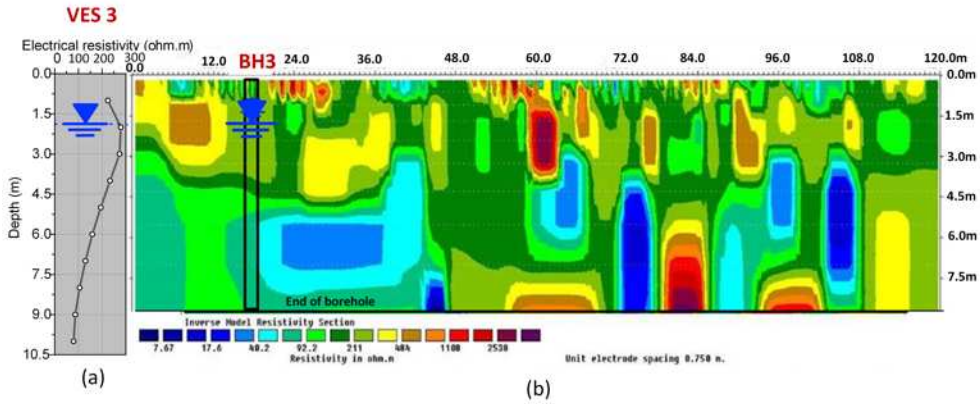


Figure 7 (a) VES and (b) Electrical resistivity model along profile line at the valley

4 CONCLUSIONS AND RECOMMENDATIONS

Borehole drilling was complemented with vertical electrical resistivity and electrical resistivity tomography geophysical survey to characterize a lateritic soil formed over phyllitic schist. The study site was delineated into three areas based on the local topography.

1. The chemical analysis of samples of the soil showed that the material in the upper and middle slopes were a lateritic, while the profile in the valley was a non-lateritic.
2. The geotechnical profiles obtained by interpolation of the borehole logs showed that the upper and middle slopes were a clayey sand formation of intermediate plasticity underlain by two silty sand formations of intermediate to high plasticity, while in the valley it was non-plastic sand underlain by a saturated silty sand of intermediate plasticity
3. The ERS profiles showed a highly heterogeneous geo-electric profiles with values to the left different from values to the right of the boreholes.
4. The geotechnical profiles obtained by interpolation of the borehole logs do not capture the heterogeneity in the resistivity values suggested in the ERT.
5. The findings of the study show that the geotechnical profiles obtained by interpolation of borehole log data alone does not capture the variation in resistivities provided by the ERT and points to the inadequacy of relying on the geotechnical data alone in interpreting the subsurface profiles.

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