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Integration of Geophysical (Vertical Electrical Sounding) and Geotechnical Data for Subsurface Characterization of Materials Within the University of Ibadan, Southwestern Nigeria

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Abstract—In terrains where weathering and lithological variability can significantly affect engineering conditions, precise subsurface characterization becomes essential for foundation design. In this study, Vertical Electrical Sounding (VES) and laboratory geotechnical investigations have been used to characterize various locations within the University of Ibadan, southwestern Nigeria. Six VES stations were surveyed using the Schlumberger array method while representative soil samples were tested for moisture content, particle size distribution, atterberg limits, specific gravity, compaction tests, CBR value, direct shear test and unconfined compressive strength (UCS). Four geoelectric layers of topsoil, lateritic/clayey material, weathered basement and fresh basement were interpreted through the use of VES. The resistivities of these materials were; 71-98 Ωm, 172-250 Ωm, 435-640 Ωm and 1,265-1,765 Ωm for topsoil, lateritic/clayey material, weathered basement and fresh basement respectively. Thicknesses of weathered basement were 8.5-10.4 m and fresh basement occurred at about 14.6-16.2 m. The soils are predominantly sandy, with about 95.5% passing 4.75 mm sieve and 2.88% passing 0.075 mm sieve. Moisture contents ranged from 12.88-17.13%, liquid limit was between 36-44%, plasticity index from 15-19% and specific gravity of 2.51-2.58. The Maximum Dry Density and Optimum Moisture Content ranged from 2.00-2.03 g/cm³ and 7.84-8.46% while the California Bearing Ratio (CBR), cohesion, friction angle and UCS values ranged from 5.41-7.72%, 4.53-5.93 kPa, 29.54-30.14° and 39.70-41.74 kPa, respectively. The results indicate a laterally variable weathering profile and relatively weak near-surface engineering characteristics. Integrated VES and geotechnical investigation provides a more reliable basis for foundation assessment than either method alone.

Keywords— Vertical Electrical Sounding; Subsurface Characterization; Maximum Dry Density; Friction Angle.

I. INTRODUCTION

The performance and longevity of civil infrastructure are heavily dependent on the engineering characteristics and spatial variability of the subsurface material at the site. Proper characterization of the subsurface condition, therefore, becomes an essential requirement for designing a suitable foundation and infrastructure because the variability of the soil or rock material influences bearing capacity, settlement, shear strength, drainage, and overall structural performance [1,2]. The conventional geotechnical investigation using boreholes, test pits, sampling, and laboratory testing gives direct measurement of important engineering properties but it is a discrete spatial technique [1,2]. Consequently, isolated sampling alone may not sufficiently describe the lateral variation of the subsurface material.

Geophysical survey complements the geotechnical investigation by investigating the physical properties of the subsurface materials over wider spatial extents. Resistivity techniques are particularly useful as they may reveal lithological contrasts, moisture, porosity, clay content, saturation, and degree of weathering based on contrast in resistivity [3,4]. Vertical Electrical Sounding (VES) is widely utilized for determining vertical variation in subsurface resistivity and estimating thickness and geometry of weathered and competent basement material [3,4]. Interpretation of resistivity survey is, however, non-unique because different lithological combination, pore fluid condition, porosity, and clay content may produce similar resistivity values [3,4]. Therefore, geotechnical information is necessary for engineering interpretation.

Combining geophysical and geotechnical survey gives an integrated approach for subsurface investigation. Geophysical surveys yield data on the continuity, stratigraphy, and variation of subsurface materials, while geotechnical tests give direct information on soil engineering characteristics. The application of this approach has been shown in studies conducted in crystalline basement areas of southwestern Nigeria where geophysical and geotechnical investigation of subsoil competence and foundation integrity was conducted [5]. Similarly, regional studies of lateritic soils along the Ibadan-Oyo corridor have indicated the variability of CBR of the soils [6].

The University of Ibadan is located in the Precambrian Basement Complex of southwestern Nigeria. Based on published geological studies, the University of Ibadan is characterized by rocks including quartzite, quartz schist, banded gneiss and augen gneiss with weathering and structural variations resulting in subsurface heterogeneity [7]. In general, the Ibadan Basement Complex consists of gneisses, quartzites, schists and granites which are products of a complicated Precambrian geological history [7,8].

Geological heterogeneity has direct implications for engineering applications. Weathering can result in soil layering such that top soil, lateritic soil and weathered basement underlie the relatively competent crystalline rock. These layers will differ in thickness and engineering properties from place to place in space.

Although geophysical and geotechnical methods have been used in southwestern Nigeria, the requirement for site-specific datasets which relate the geoelectric layering to soil engineering properties still exists within the University of Ibadan environment.

This study integrates VES and geotechnical data to investigate selected subsurface soil layers within the University of Ibadan environment. The specific objectives were to:

1. determine the subsurface resistivity distribution and geoelectric layering using VES;
2. determine selected index and engineering properties of representative soil samples; and
3. integrate the geophysical and geotechnical results to assess subsurface competence and implications for foundation suitability.

II. LITERATURE REVIEW

2.1 Subsurface Characterization and Site Investigation

Subsurface characterization is the identification of materials, thicknesses of layers, weathering conditions, groundwater conditions and geotechnical parameters for construction purposes [1,2]. The naturally heterogeneous soil and rock masses exhibit a wide variation in their geotechnical behavior over relatively small distances.

While conventional subsurface investigations through drilling, trial pits and laboratory tests form the foundation of subsurface information, they lack the capability of defining lateral continuity due to their discrete nature [1,2]. Geophysical techniques form an important tool in the provision of spatial information of the subsurface [3,4].

Thus, a combination of both direct and indirect methods of investigations is extremely helpful in the presence of considerable geological heterogeneities.

2.2 Geotechnical Properties Relevant to Engineering Behaviour

Properties like moisture content, particle size distribution, Atterberg limits, and specific gravity tell us about the composition, classification, and consistency of soils [1,2]. Properties like compaction, CBR, shear strength, and UCS provide better understanding of the behavior of soils under construction conditions and loads.

The natural moisture content affects soil density, consistency, and strength. Particle size distribution tells us about the gradation of soils and helps in their classification. The Atterberg limits describe the consistency of fine-grained soils and serve as indicators of plasticity [2].

Compaction characteristics are very important during earth works because of the relation between the moisture content and dry density affect strength, compressibility, and permeability. Maximum dry density and optimum moisture content are determined from standard laboratory tests [14].

CBR is the indicator of penetration resistance and used in pavement and subgrade investigations [15]. The shear strength is important for foundation, slope, and retaining structures whereas UCS tells us about the compressive resistance of soils [1,2,16].

2.3 Electrical Resistivity Investigation

Electrical resistivity techniques determine the variation in resistivity of the subsurface formation by studying the reaction of the earth formation to the application of current. The various factors that affect resistivity include lithology, pore fluid conductance, porosity, saturation, clay content, and weathering.

The technique has advantages for engineering studies due to the rapidity with which resistivity data can be collected and interpreted to determine subsurface layering. Nevertheless, resistivity does not offer lithological identification uniquely. Hence, a geological considerations and geotechnical data, where available, should be used in the interpretation process.

2.4 Vertical Electrical Sounding

VES examines variations in apparent resistivity with increase in electrode separation. VES is especially suitable for layered subsurface conditions since increased current-electrode separation leads to deeper penetration [3,4].

The Schlumberger configuration utilizes two outer current electrodes and two inner potential electrodes. Apparent resistivity is determined based on the measurements of the current and potential difference with the help of corresponding geometric factor.

The VES analysis includes matching and inversion procedures in order to obtain estimates of resistivity and thickness of layers. Since different layered earth models can produce the same apparent resistivity curve, the interpretation is inevitably non-unique [3,4].

2.5 Integration of Geophysical and Geotechnical Methods

While geophysical and geotechnical studies offer complementary types of information, the former is indirect in terms of measurements, whereas the latter is direct in its measurement but is often done at specific points rather than over space [3-5].

The usefulness of integrating the two approaches has been illustrated in southwestern Nigeria through Olayanju et al. [5]'s application of the integrated approach in characterizing a crystalline basement environment and assessing the condition of foundations through the interpretation of geoelectric stratigraphy with soil parameters.

In this current research, the same general concept has been adapted for some chosen locations within the University of Ibadan environment and a range of engineering tests have been incorporated.

2.6 Previous Studies

Earlier studies have proved the relevance of using the methods of electrical resistivity as well as geophysical–geotechnical integration on Basement Complex formations in southwest Nigeria [3–5]. Olayanju et al. [5] were able to classify four geoelectric units and emphasized the necessity of integration between geophysical and geotechnical data while evaluating the foundation on crystalline basement formation.

On the other hand, Fasanmade et al. [6] studied the sub-base materials along the Ibadan–Oyo Road and recorded considerable variations in the CBR values of the materials.

2.7 Research Gap

Previous studies have shown the effectiveness of geophysical and geotechnical surveys in southwestern Nigeria. Nevertheless, there is still a lack of studies conducted using the combination of VES and laboratory surveys tailored to the environment of the University of Ibadan with geoelectric layering correlated with various engineering parameters.

Moreover, the non-uniqueness of the interpretation of the resistivity data complicates the application of the resistivity values as indicators of the engineering competence. This study tries to fill this gap by correlating the results of VES and laboratory surveys.

III. MATERIALS AND METHODS

3.1 Study Area

The study was carried out in the University of Ibadan, Ibadan, Oyo State, south western part of Nigeria. The study area lies within the Precambrian Basement Complex formation. Generally, the wider Ibadan area is composed of quartzite, quartzite schists, gneisses and migmatites while the University area consists of quartzite, quartzite schists, banded gneisses and augen gneisses [7,8].

The area has a tropical weathering climate. Tropical weathering of crystalline basement rocks gives rise to different thicknesses of soil, laterite and weathered rock overlying the relatively strong basement rocks.

3.2 Research Design

Geophysical and geotechnical integration was used for the design process. The investigation included:

- a reconnaissance survey;
- the selection of six locations for investigation;
- VES data acquisition;
- soil sample collection;
- lab tests;

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- geophysical and geotechnical data processing independently; and
- integration of data interpretations.

The six locations of investigation were chosen to cover the space of the study environment and compare geoelectric and geotechnical properties.

3.3 Geophysical Investigation

3.3.1 Vertical Electrical Sounding

VES measurements were done on six stations using the Schlumberger array method. Four electrodes were set up such that they were almost in a straight line; the outer electrodes acted as current electrodes while the inner electrodes were potential electrodes.

The distance between the current electrodes was increased gradually to increase depth penetration. Current and potential differences at each distance were measured. Apparent resistivity was determined from:

$$\rho a = K\frac{\Delta V}{I}$$

Where:

ρa=Apparent resistivity(Ωm)

K= Geometric factor

ΔV =Measured potential difference

I=Injected current

The methodology follows established electrical-resistivity procedures [3,4].

3.3.2 VES Data Processing

The apparent resistivity values were graphed versus half current electrode spacing (AB/2). The profiles were interpreted by means of layered earth modeling and inversion [3,4,8].

The models thus derived provided estimates of:

- resistivity of layers;
- thickness of layers;
- depths to interface points; and
- depth to the inferred fresh basement.

The geophysical interpretations were later compared with the laboratory data.

3.4 Geotechnical Investigation

Soil samples were obtained from the chosen investigation sites using proper manual sampling methods. The samples were properly labeled and taken to the laboratory for testing.

Tests carried out in the laboratory included:

- Natural Moisture Content;
- Particle Size Distribution;
- Atterberg Limits;
- Specific Gravity;
- Standard Proctor Compaction;
- California Bearing Ratio;
- Direct Shear;
- Unconfined Compressive Strength.

These tests were done using the right ASTM procedure [9-17].

3.4.1 Natural Moisture Content

Natural moisture content was established through oven-drying process according to the ASTM D2216 [9] standards:

$$w = \frac{Md}{Mw} \times 100$$

where Mw is the mass of water and Md is the mass of dry soil

3.4.2 Particle-Size Distribution

The particle size distribution was carried out using sieve analysis method as per ASTM D6913/D6913M [10]. These values were then used to find the relative proportion of sand and fine particles for USCS classification.

3.4.3 Atterberg Limits

The liquid limit and plastic limit were established following the ASTM D4318 [11] standard. The plasticity index was calculated from:

$$PI = LL - PL$$

Where;

LL is liquid limit and PL is plastic limit.

3.4.4 Specific Gravity

Soil solids specific gravity was measured through the pycnometer test method according to ASTM D854 [13].

3.4.5 Compaction

CBR test was carried out to determine the resistance to penetration of the compacted soil. This was done according to ASTM D1883 [15]. The higher corrected value which corresponds to the required penetration was selected following the test interpretation method.

3.4.6 California Bearing Ratio

Tests were conducted using the CBR test to determine the soil's penetration resistance. The test was done in accordance with the ASTM D1883 [15] standards. The higher correct value, which corresponds to the required penetration, was considered.

3.4.7 Direct Shear Test

Soil shear strength parameters were determined by direct shear tests based on the following Mohr-Coulomb theory:

$$\tau = c + \sigma \tan\phi$$

where:
τ = shear stress at failure;
c = cohesion;
σ = normal stress; and
ϕ = angle of internal friction.

The test procedure is consistent with ASTM D3080/D3080M [17].

3.4.8 Unconfined Compressive Strength

Uniaxial Compressive Strength tests were conducted on samples of cohesive soil using unconfined axial load in line with ASTM D2166/D2166M [16].

Uniaxial Compressive

$$qu = \frac{P}{Ac}$$

where P is the maximum axial load and Ac is the corrected cross-sectional area.

3.5 Integration and Data Analysis

The main part of the analysis was the comparison between the geoelectric models produced by VES and the physical characteristics obtained from the lab. The following variables were included:

- resistivity;
- layer thickness;
- depth to fresh basement;
- moisture content;
- particle size distribution;
- Atterberg limits;
- specific gravity;
- MDD;
- OMC;
- CBR;
- cohesion;
- friction angle; and
- UCS.

The analysis was mostly interpretation-based since only six sites were used for the analysis, which is a small dataset. Therefore, no predictive model could be constructed from the data.

3.6 Quality Control

Consistency check was done during field measurement, while laboratory tests adhered to standardized procedures. Maintenance and calibration of equipment were properly done, and duplicate measurements were carried out when necessary.

Numerical consistency of data was done prior to analysis. Especially, layer thicknesses were added to determine the depth of the top of fresh basement rock in VES stations.

IV. RESULTS

4.1 VES Results

Interpretation of six VES sections was done using four layers of geoelectric section comprising topsoil, laterite/clay, weathered and fresh basement rock.

Table 1: Interpreted VES parameters

VES	Layer	Resistivity (Ωm)	Thickness (m)	Interpretation
VES 1	1	98	1.2	Topsoil
	2	215	4.5	Lateritic clay
	3	520	9.3	Weathered basement
	4	1,450	—	Fresh basement
VES 2	1	76	1.0	Topsoil
	2	184	5.1	Clayey laterite
	3	460	8.5	Weathered basement
	4	1,320	—	Fresh basement
VES 3	1	88	1.4	Sandy clay
	2	250	4.7	Lateritic soil
	3	610	10.1	Weathered basement
	4	1,680	—	Fresh basement
VES 4	1	82	1.3	Clayey topsoil
	2	205	4.9	Lateritic clay
	3	575	9.6	Weathered basement
	4	1,540	—	Fresh basement
VES 5	1	94	1.1	Sandy lateritic topsoil

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	2	238	4.3	Lateritic soil
	3	640	10.4	Weathered basement
	4	1,765	—	Fresh basement
VES 6	1	71	1.5	Clayey topsoil
	2	172	5.4	Clayey laterite
	3	435	8.9	Weathered basement
	4	1,265	—	Fresh basement

The resistivities of the first layer range from 71 to 98 Ωm, with a thickness of 1.0 to 1.5 m. The second layer exhibits resistivities of 172 to 250 Ωm with thicknesses of 4.3 to 5.4 m. Resistivities in the third layer range from 435 to 640 Ωm with thicknesses of 8.5 to 10.4 m.

The calculated depths to the top of fresh basement are:

Table 2: Depths to the top of fresh basement

VES	Depth to fresh basement (m)
VES 1	15.0
VES 2	14.6
VES 3	16.2
VES 4	15.8
VES 5	15.8
VES 6	15.8

Therefore, the thickness of fresh basement varies from 14.6 to 16.2 meters.

The weathered basement is thicker at VES 5 (10.4 m) and VES 3 (10.1 m), reflecting spatial variability in the extent and depth of weathering.

4.2 Natural Moisture Content

Natural moisture content ranges from 12.88–17.13%.

Table 3: Natural moisture content

Location	Sample A (%)	Sample B (%)	Mean (%)
1	12.88	13.51	13.20
2	14.84	14.80	14.80
3	16.32	16.30	16.30
4	13.54	13.52	13.50
5	15.88	15.93	15.90
6	17.07	17.13	17.10

Location 1 has the minimum moisture content, while Location 6 has the maximum.

4.3 Grain-Size Distribution

Soils consist mainly of sand-size particles. About 95.2 to 95.7 percent of the soil samples pass the 4.75 mm screen, while 2.

Table 4: Grain-size distribution

Sieve size (mm)	L1 (%)	L2 (%)	L3 (%)	L4 (%)	L5 (%)	L6 (%)	Mean (%)
4.75	95.60	95.30	95.70	95.50	95.20	95.70	95.50
2.00	79.30	78.90	79.60	79.30	78.40	79.40	79.15
0.850	43.60	43.10	44.70	43.60	42.70	43.30	43.50
0.425	19.40	18.40	19.80	19.20	18.00	19.00	18.97
0.212	9.30	8.00	9.40	8.90	7.70	8.70	8.67
0.150	6.80	5.40	6.70	6.30	5.20	6.20	6.10
0.075	2.40	2.20	3.40	3.10	2.10	3.00	2.88

As less than 5% passes through the 0.075 mm sieve, the soil samples belong to the category of clean sand of USCS. As the Cu values are found between 5.20 – 5.60, these do not meet the criteria of well-graded sand. These soils can therefore be classified as poorly graded sands (SP).

4.4 Atterberg Limits

Table 5: Atterberg-limit results

Sample	LL (%)	PL (%)	PI (%)
S1	38	22	16
S2	42	24	18
S3	36	21	15
S4	44	25	19
S5	40	23	17
S6	41	24	17

LL varies between 36-44%, PL varies between 21-25%, and plasticity index between 15-19%. Sample S4 has the maximum LL and PI, while sample S3 has the minimum values.

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Since all bulk samples have less than 5% of material passing through the 0.075 mm sieve, then the Atterberg Limit values obtained cannot be considered as proof of their being clay-type soils based on the USCS classification.

4.5 Specific Gravity

Table 6: Specific gravity

Location	Sample A	Sample B	Mean Gs
1	2.44	2.58	2.51
2	2.50	2.56	2.53
3	2.53	2.61	2.57
4	2.51	2.57	2.54
5	2.55	2.61	2.58
6	2.52	2.58	2.55

The mean value for specific gravity lies between 2.51 and 2.58, which shows that there is not much variation in space with regard to solid particles of these materials.

4.6 Compaction Characteristics

Table 7: Standard Proctor compaction results

Location	MDD (g/cm^3)	OMC (%)
1	2.00	8.38
2	2.03	7.84
3	2.01	8.46
4	2.01	8.46
5	2.00	8.46
6	2.01	8.46

The values for MDD lie within the range 2.00-2.03 g/cm^3 and OMC lies within 7.84-8.46%. This shows similarity in terms of

4.7 California Bearing Ratio

Table 8 : CBR results

Location	2.5-mm Top (%)	2.5-mm Bottom (%)	5.0-mm Top (%)	5.0-mm Bottom (%)	Adopted CBR (%)
1	3.78	3.93	6.31	5.51	6.31
2	3.47	3.70	5.81	5.96	5.96
3	4.23	4.46	6.91	7.11	7.11
4	3.10	3.32	5.21	5.41	5.41
5	4.61	4.83	7.52	7.72	7.72
6	4.00	4.23	6.61	6.81	6.81

Adopted CBR values range from 5.41% to 7.72%. The highest CBR value is at Location 5, and the lowest is at Location

4.8 Direct Shear Strength

Table 9: Shear-strength parameters

Location	Regression equation	c (kPa)	tan φ	φ (°)
1	$\tau = 5.09 + 0.5778\sigma$	5.09	0.5778	30.02
2	$\tau = 5.93 + 0.5666\sigma$	5.93	0.5666	29.54
3	$\tau = 5.00 + 0.5778\sigma$	5.00	0.5778	30.02
4	$\tau = 5.01 + 0.5805\sigma$	5.01	0.5805	30.14
5	$\tau = 4.53 + 0.5750\sigma$	4.53	0.5750	29.90
6	$\tau = 5.83 + 0.5778\sigma$	5.83	0.5778	30.02

Values of cohesion obtained were in the range of 4.53–5.93 kPa, whereas those of friction angle were 29.54–30.14°. Narrow range of friction angles shows similarity of friction behaviour of soils from different locations studied.

4.9 Unconfined Compressive Strength

Table 10: UCS results

Location	Diameter (mm)	Initial height (mm)	Final height (mm)	Maximum load (kN)	UCS (kPa)	Failure mode
1	50	95	92	0.080	40.72	Shearing
2	50	95	92	0.079	40.21	Shearing
3	50	95	91	0.081	40.72	Shearing
4	50	95	92	0.080	40.72	Shearing

5	50	95	91	0.078	39.70	Shearing
6	50	95	92	0.082	41.74	Shearing

UCS ranges from 39.70–41.74 kPa. Location 6 has the highest measured UCS, whereas Location 5 records the lowest.

V. DISCUSSION

5.1 Geoelectric Characteristics and Subsurface Architecture

VES analysis shows a four-layer geoelectrical sequence including topsoil, laterite/clay, weathered basement and fresh basement. This geoelectrical sequence correlates well with the structure of weathering common in the area of crystalline basement in Southwestern Nigeria [3–5].

The low resistivity of near-surface layers when compared with the basement may be explained by such factors as moisture, presence of clay minerals, porosity and weathering. High resistivity is observed in the fresh basement and its values range between 1,265 Ωm and 1,765 Ωm.

However, this interpretation may not be considered as a lithological one since resistivity depends on several geological and hydrogeological parameters [3,4]. The results of geotechnical analysis thus serve as an important boundary for VES interpretation.

The thickness of the weathered basement varies from 8.5 m to 10.4 m. It is maximal in the case of VES 5, followed by VES 3. This means that there is spatial variability of weathering depth.

The depth to fresh basement varies between 14.6 m (at VES 2) and 16.2 m (at VES 3). It confirms the unevenness of basement surface.

5.2 Geotechnical Characteristics

The natural moisture content is within the range of 12.88%-17.13%. The elevated moisture contents of Locations 3, 5 and 6 could be associated with different drainages, pore structure and soil moisture retention properties.

Based on the particle-size distribution test data, one can conclude that the studied soils consist mainly of sand particles. The percentage passing through the 0.075-mm sieve is quite small (2.88%), which means the presence of very low content of fines. The coefficients of uniformity less than 6 prove that the tested sands do not correspond to the definition of well-graded sand according to the USCS system [12].

It is necessary to interpret the values of Atterberg limits cautiously. Despite the fact that PI varies from 15% to 19%, less than 5% of the total volume of bulk samples passes the 0.075-mm sieve. Hence, the plasticity values refer to the fine fraction of the soil. This information is significant, because it is incorrect to describe the whole mass of soils as clayey based on PI values.

The specific gravities are relatively stable, which means identical solid-particle characteristics.

5.3 Compaction and CBR Behaviour

For MDD and OMC, values were observed between 2.00–2.03 g/cm³ and 7.84–8.46% respectively. There is little variation which shows uniformity in the compaction characteristics.

The CBR readings exhibited more spatial variations compared to those of compaction. The adopted values varied from 5.41–7.72%. Highest CBR value was recorded at Location 5 while the lowest was recorded at Location 4.

These CBR readings are indicative of low penetration resistance. The significance of these values will depend on the application and moisture conditions. CBR can therefore be considered as a measure of subgrade/sub-base material performance and not the foundation bearing capacity.

This is supported by Fasanmade et al. [6] who established the existence of variations in CBR behavior of lateritic materials in the Ibadan-Oyo Road.

5.4 Shear Strength and UCS

The cohesion values obtained from the direct-shear testing are between 4.53 and 5.93 kPa and the friction angles are 29.54-30.14º. The similarity in the friction angles is an indication of similarities in the frictional properties of the soils sampled.

The low values for cohesion can be attributed to the mostly granular nature of the soils based on their particle size distributions. The higher values for friction angle indicate their significance in resisting shearing at increased normal loads.

UCS values lie between 39.70 and 41.74 kPa with very little variation in space. This indicates that there is relative similarity in the compressive characteristics of the soils tested.

Direct shear test and UCS measure two different aspects of the soil strength and cannot be considered as equivalent.

5.5 Integrated Geophysical–Geotechnical Interpretation

The major significance of the research is in the complementary characteristic of the two datasets.

The VES data show the stratigraphic structure of the subsurface comprising of near surface soil, lateritic layer, weathered basement and fresh basement. The geotechnical data give information about the engineering properties of the materials directly from the samples.

The lower resistivity of the near surface materials is in agreement with the fact that the near surface materials have high degree of weathering and moisture effects, whereas the high resistivity of the deeper layer is in conformity with the fact that the basement materials are less weathered.

But there cannot be an exact linear relationship established between the resistivity and CBR, UCS, moisture content and shear strength from the existing dataset at six locations. Resitivity depends on many factors simultaneously. Hence, the current study is useful in making correlation between geophysical and geotechnical properties qualitatively.

5.6 Engineering Implications

The study reveals that there is a laterally variable weathering regime in the subsurface. There are thin topsoils, with a thickness of 1.0 to 1.5 m and which cannot necessarily be considered good founding horizons.

The depth of penetration of the laterites and weathering regime is quite deep, since the fresh basement layer is met at about 14.6 to 16.2 m deep. The thickness of the weathered profile does not necessarily indicate an unsuitable area for construction of foundations. Suitability for foundation depends on the strength, compressibility, density, moisture content, loading, and actual depth of founding.

The CBR of 5.41–7.72% indicates moderate penetration resistance and suggests that the materials need treatment if they are going to be used in heavily loaded applications.

The fresh basement layer is the most resistive rock layer, but resistivity alone is not enough to determine the permissible bearing pressure. Geotechnical investigation and analysis are essential in this regard.

This integrated approach agrees well with the findings of other studies conducted in southwestern Nigeria [5].

VI. CONCLUSIONS

A joint VES and geotechnical study was carried out at six sites selected around the University of Ibadan environment to identify the subsurface conditions and their engineering implications.

The VES study revealed a consistent four-layer geoelectric configuration consisting of topsoil, lateritic/clayey material, weathered basement and fresh basement. Topsoil resistivity varies between 71-98 Ωm, lateritic/clayey material between 172-250 Ωm, weathered basement between 435-640 Ωm and fresh basement between 1,265-1,765 Ωm.

Weathered-basement thickness varies between 8.5-10.4 m, while depth to fresh basement is 14.6-16.2 m. The maximum weathered-basement thickness is observed at VES 5, indicating lateral variability in weathering profile.

The geotechnical results show that the tested soils are mostly sand-sized particles, with about 95.5% passing the 4.75-mm sieve and just 2.88% passing the 0.075-mm sieve on average. The reported coefficient of uniformity indicates the prevalence of poorly graded sand within the USCS system.

Natural moisture content varies between 12.88-17.13%, liquid limit between 36-44%, plastic limit between 21-25%, and plasticity index between 15-19%. Since bulk fines percentage is less than 5%, the results of Atterberg-limits test should be considered as those of fine particles instead of being used as the main basis of soil classification.

Specific gravity varies between 2.51-2.58. Maximum dry density ranges between 2.00-2.03 g/cm^3, and optimum moisture content varies between 7.84-8.46%, showing fairly consistent compactibility.

The adopted California bearing ratio (CBR) values range between 5.41-7.72%. The cohesion obtained from direct-shear tests is 4.53-5.93 kPa and the internal angle of friction is 29.54-30.14°, while unconfined compressive strength (UCS) is between 39.70-41.74 kPa.

Thus, the above results have shown that both VES and geotechnical testing can provide complementary information. In particular, VES is an efficient tool for revealing spatial and vertical configuration of the subsurface layers, while laboratory tests provide direct data on engineering behavior of the subsurface layers.

As a result of the above study, it has been established that the study environment has spatially variable, yet recognizable subsurface conditions. The observed variability of weathered-zone thickness and engineering properties stresses the necessity of conducting foundation investigation in each particular case. Resistivity and basement depth should be regarded as additional information, not substitutes of geotechnical assessment.

VII. RECOMMENDATIONS

1. Site-specific investigations of foundation should be carried out.
   The wide spread of thickness variation of weathered basement and its geotechnical characteristics indicates that generalized soil profile should not be adopted through the whole research area.
2. VES should be combined with the direct investigations for the significant structures.
   Boreholes, trial pits and laboratory tests should be employed to confirm geoelectrical interpretation and determine engineering parameters at site of proposed foundation.
3. The near-surface materials should be checked prior to construction of foundation.
   Relatively small CBR values show that the near-surface materials should not be automatically considered suitable for engineering purposes under heavy loads.
4. Compaction and water content control should be done during earthworks.
   Laboratory value of MDD and OMC should be taken into account during field compaction control.
5. Unsuitable near-surface materials should be dealt with where required.
   Depending on requirements of particular project, possible measures may include controlled compaction, removal and replacement of the material, stabilization, improved drainage, alternative foundation system, etc.
6. Additional geophysical investigations should be performed for major projects.
   Additional VES points and two-dimensional electrical resistivity imaging can provide more accurate information about lateral variations of basement and possible structural discontinuities.
7. Further investigations should involve larger paired set of data.
   More VES points and geotechnical investigations will allow conducting statistically significant analysis of correlation and regression between resistivity and engineering parameters.
8. Foundation design should not be performed solely on basis of resistivity.
   Allowed bearing capacity, settlement, groundwater level, structural loads, engineering properties of actual founding layer should be analyzed in the final design.

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