Evaluation of hydraulic conductivity of lateritic soils using integrated approach: southwestern Nigeria case study

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Abstract

The source of groundwater seepage problem being experienced by some engineering buildings in a part of southwestern Nigeria was investigated by carrying out comparative study of the hydraulic conductivity (K) of the soil types underlying the area using integrated approaches involving geotechnical and geophysical methods.
Soil samples were collected from six different towns on which standard geotechnical tests including natural moisture content, grain size distribution, linear shrinkage, specific gravity, liquid and plastic limits, compaction, triaxial and K test were carried out. Also, geophysical data were acquired at seventy-two locations using Schlumberger array with a current electrode spacing of 40m. The resistivity data obtained were subsequently inverted to obtain the subsurface 2D hydraulic conductivity section.
The results obtained imply that the soil types investigated is semi-pervious with K values ranging from 1.06 x 10^{-5} to 5.71 x10^{-5}cm/s. These values suggest moderate groundwater flow which might account for the seepage that was observed. Four lithologies (lateritic topsoil, clayey-sand, sandy-clay and fractured/weathered bedrock) were delineated. The geotechnical analysis result suggests the soil investigated could be classified as poorly graded sandy-clay and/or silty-clay. This soil exhibit plasticity index ranging from 12.72 to 19.75%, with specific gravity ranging from 2.47 to 2.73; the maximum dry density (MDD) varies from 1699.5 kg/cm^3 to 1915kg/cm^3 and the optimum moisture content (OMC) ranges from 12.05% to 16.32%.The result of the t-test results performed implied that at 95% t–confidence level, there is a good correlation between the results obtained from both approaches employed.

Keywords: *Geotechnical Tests; Groundwater Seepage; Hydraulic Conductivity; Resistivity; Soil.*

1. Introduction

Lateritic clay has been found to be one of the most abundant soils in the tropical part of the world. Its availability has enhanced its usage as materials for the construction of roads, airfields, earth dams, and foundation of structures. Engineers are primarily interested in a soil's mechanical properties such as strength, stiffness and permeability.
The hydraulic conductivity (K) of soils is a key parameter that is required for analysis and design of numerous civil engineering works such as seepage, groundwater development, consolidation, drainage, contaminant studies. The hydraulic conductivity of saturated soils varies significantly from approximately 10^{-13} m/s for high plasticity clays to 1 m/s for clean, uniformly graded, coarse gravels. DeGroot et al. (2012) showed that this large range in values has resulted in the development of numerous field methods that cater to the soil type being tested and the anticipated hydraulic conductivity.
In civil engineering practice, geotechnical parameters such as permeability of rocks and soils are required for subsurface characterization. It is commonly determined from geotechnical approach such as pump tests, grain size analysis, which involves drilling or digging in order to obtain samples; which over a large area are cumbersome, time-consuming and expensive.

Several approaches have been used to determine the hydraulic conductivity of both the unsaturated and saturated soils found in the tropical and temperate regions of the world. For example, Yu et al. (2013) used an integrated approach to investigate the hydraulic conductivity of clay soil. Their result showed good degree of correlation among methods. Odong (2013) and Justine (2007) showed that empirical technique is fast and efficient for determining hydraulic parameters of soils using the grain size analysis method. They suggest that unless the appropriate robust empirical such as the Kozeny-Carman formula method is employed, the hydraulic conductivity values estimated may be either underestimated or overestimated. Sobotkova et al. (2011) used inverse modeling and column experiment to derive the hydraulic conductivity of the oxisol soil found in the tropical area of Hawaii, USA. They obtained results that are consistent with the tropical soils. Edoga (2010) conducted saturated hydraulic conductivity using the constant head permeameter method at four sites with samples taken at different depths (15, 30, 45, 60 cm) at Samaru, Zaria. He used the redefined Kozney Carman model and Yannopoulos equations to predict hydraulic conductivity and the results obtained from the laboratory technique were compared favourably with the Kozney-Carman and Yannopoulos prediction models. However, Shevnin et al. (2006) reported on the estimation of hydraulic conductivity in soil using the resistivity data (geophysical method).They confirmed the influence of the clay contents on the hy-

draulic conductivities determined. But Xu and Dong (2004) proposed the fractal technique for predicting the hydraulic conductivity of unsaturated porous media for geophysical, geotechnical and agricultural applications. Simunek and Genuchten (1996) adopted an inverse modeling procedure to estimate the soil hydraulic characteristics of a two-layered soil system—soil surface crust and subsoil—from data obtained during a tension-disc infiltration experiment. Similarly, Kodesová et al. (1998) and Kodesová et al. (1999) presented results of field testing of inverse modeling in two types of soil using the cone penetrometer method.

However, the geophysical approach such as electrical resistivity sounding, which is non-invasive, requires no perforation, and can produce information faster than drilling. There have been several attempts in the past to obtain quantitative information on relationship between hydraulic conductivity and resistivity. Katsube and Hume (1987), Nishimakiet al. (1999), and Suzuki (2002) have all shown that rock permeability is proportional to rock resistivity.

On the other hand, Matsui et al. (1977) showed that resistivity increases with increasing hydraulic conductivity at low to moderate values of resistivity, while resistivity increases with decreasing hydraulic conductivity where the range of resistivity is moderate to high, in granitic rocks. Sudoet al. (2004) showed that the relationship between resistivity and hydraulic conductivity of granitic rocks can be interpreted with crack models.

The thrust of this research work is the investigation of the hydraulic properties of the subsoil existing in six major towns that are located in parts of Ile-Ife, Akure, Ibadan, Ondo, Ogbomoso and Ilesha, southwestern Nigeria (Fig. 1) using combined geotechnical and geophysical approaches. For this study, geophysical method was considered as an alternative cost effective method for potential groundwater seepage mapping in an area where groundwater seepage is threatening the foundation of existing engineering buildings.
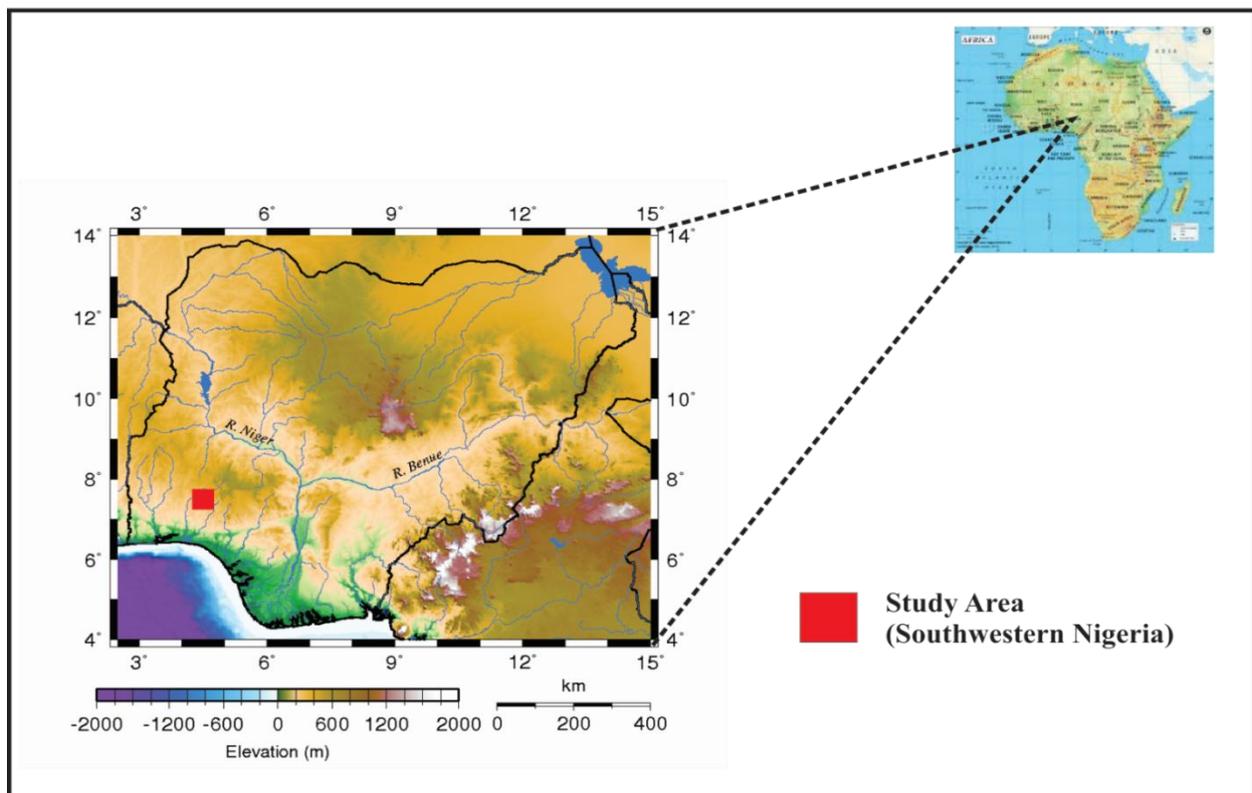

Fig. 1: Location Map of Study Area in South western Nigeria

2. Geology of the area under study

The study area is underlain by the Precambrian Basement complex rocks of Southwestern Nigeria. The local geologic units identified in the study area are the Migmatitic-Gneisses. They are composed of three main components namely: Early Gneiss, Mafic-Ultramafic Bands and Granitic or Felsic Component. Rahaman (1988) classified the major lithological rock units of the complex into two major groups: gneisses and schists, with minor occurrence of intrusive mafic/ ultramafic rocks that probably represent remnants of an oceanic assemblage. Due to intense tropical weathering, the bedrock weathered into thick regolith overburden materials that vary from lateritic clay, clayey sand, to sand (Adepelumi et al., 2001). There are also minor Pegmatite vein and quartz vein intrusions. Field relationship shows that the granite gneiss which forms the large residual hills in addition to a few low-level outcrops is intrusive into the grey gneiss. This interpretation is based on the occurrence of grey gneiss in the granite gneiss. All the rocks are either weakly deformed and as a result show microfolds and microfaults.

3. Methodology

Thirty-six test pits, each 3m deep were dug at six selected towns (Ile-Ife, Akure, Ibadan, Ondo, Ogbomoso and Ilesha) in southwestern Nigeria. The sampling locations is at the geographic coordinates (Latitude and Longitude)7°30'51"N/4°29'35"E, 7°24'15"N/5°17'20"E,   8°12'30"N/3°11'28"E, 7°10'54"N/4°58'18"E,8°08'19"N/4°15'13"Eand

7°37'43"N/4°44'30"E. At the sites, soil samples were collected at regular intervals of 0.6m, 1.2m, 1.8m, 2.4m and 3.0m vertically downward in the pits. The soil samples were subjected to geotechnical laboratory tests in accordance with BS1377 (1990) standard to obtain their characteristics geotechnical and soil profile properties. The laboratory tests performed on air dried soil samples are: grain size distribution, specific gravity, liquid and plastic limits, compaction, triaxial test and hydraulic conductivity of the lateritic soil samples.

For the electrical resistivity method, the Schlumberger configuration was used throughout the survey with the half-current electrode spacing (AB/2) used varying from 1m to 40m. A total of seventy-two (72) VES points along eighteen(18) traverses were

occupied.The apparent resistivity data obtained at each of the 72 VES stations were plotted against the half-current electrode spacing (AB/2) using Pirttijärvi (2013 version) electrical sounding software. The model description generated the resistivity value of soil layers, the layer thickness and the depth at each VES stations considered which helped in deciphering the soil layers at the survey site.

In order to evaluate the relationship between resistivity and hydraulic conductivity in the study area and obtain insight about the hydrological conditions vis-à-vis groundwater flow regime in the area, the apparent resistivity data acquired were inverted to create a model of 2D subsurface resistivity sections that were transformed to a 2D permeability section using DIPRO (2012 version) inversion program. The empirical formula employed was established by Ogata et al. (1992) and Sudo et al. (2004) for estimating the hydraulic conductivity (K) of clayey sand/clay and lateritic clay given as;

$$K = 3.545 \times 10^{-11} \times \rho^{3.9072}$$

Where K= hydraulic conductivity in cm/sec, and ρ = apparent resistivity in Ohm-m.

For the purpose of establishing the relationship between the resistivity and the hydraulic conductivity (K) existing for the area of study; the K values obtained using the K formula above were plotted against the resistivity values retrieved from the inverted resistivity along traverses 1, 2 and 3 respectively.

4. Results and discussions

4.1. Geoelectrical section along the traverses

For the six towns investigated, the subsurface geology delineated has similar lithology (soil types) with minor variation of thicknesses and resistivity values. The subsurface Geoelectrical sections along three traverses (Traverses 1, 2 and 3) are presented in Fig. 2.These sections revealed that there are four distinct geological layers at the survey sites; lateritic top soil, clayey-sand, sandy-clay layer and weathered bedrock and bedrock

The top soil has resistivity values ranging from 41 Ohm-m to 909 Ohm-m with a thickness layer range of 1.30m – 2.83m. This layer consists of lateritic/clayey top soil. The clayey-sand has resistivity values ranging from 94.7 to 424.5 Ohm-m with a thickness of 1.50m -3.89m. The third layer resistivity value varies from 187.1-3736.3 Ohm-m and its thickness is between 1.48m - 7.75m, this is the sandy-clay layer. The fourth layer has resistivity value as low as 50.7 Ohm-m and as high as 5645.1Ohm-m, this represents the fractured bedrock and bedrock respectively. Between VES 4 and 6, a depression zone which possibly contains conductive liquid was observed. Forward modelling results generated by Adepelumi et al. (2006) indicates that such depression is likely to be fractured bedrock in which water may have accumulated.

4.2. Hydraulic conductivity and resistivity of soil

Figure 3shows the hydraulic conductivity sections obtained from the transformation of the resistivity data obtained along the traverses. Four distinct hydrologic regimes labelled A, B, C and D are recognisable in the three sections. The regime corresponds to the subsurface lithology existing in the area under study. The weathered/fractured layer constitutes the main aquifer which serves as a conduit for groundwater seepage in the area.

Generally, from the inverted resistivity result for traverse 1 (Fig. 3a), the K values retrieved vary from 3.3 X 10^{-9} to 2.2 cm/s with a root mean square (rms) error of 7.25%. The topsoil marked A is the most permeable with 2.2 cm/s. It is apparent that the bedrock depression zone has high K which possibly results in high ground water flow. For traverse 2 (Fig. 3b), The K values varies from 5.4 x 10^{-10} to 5.6 cm/s with arms error of 5.19%. The K value around the basement depression varies from 2.8 to 5.6 cm/s.These values suggest that the depression area is a good aquifer; hence it might

account for the continuous flow of ground water observed in the region. However, for traverse 3 (Fig. 3c), the K values (1.2 x10^{-7} to 1.5 x10^{-3} cm/s) obtained along this traverse is however low compared to traverses1 and 2. The rms error associated with this inverted result for traverse 3 is 2.58%. Since the K value obtained from the inversion for traverses1 and 2 is higher than traverse 3, this possibly suggest that the soil beneath traverse 3 is more saturated.

The relationship existing between resistivity (ρ) and hydraulic conductivity along traverses 1, 2 and 3 respectively is presented in Fig. 4. It is obvious that a distinct linear relationship exist between the derived K and ρ values at all the locations. The geologic implication of this is that the soil types are strongly influenced by the K values.This suggests that a decrease in hydraulic conductivity would lead to increase in resistivity and vice versa.

4.3. Statistical t-test for comparison of hydraulic conductivities

When hydraulic conductivities (K) measurements are made using different techniques, it is important to determine whether the K values estimated are different between sample locations. To investigate this effect, statistical tests were used. The t-test compares the actual difference between two means of the K values in relation to the variation in the data expressed as the standard deviation of the difference between the means of the K.

The K values are considered significantly different if the 95% confidence interval for their averages overlap (t test with a=0.05). For this purpose, the statistical t-test was conducted on the K values obtained from both the geophysical and geotechnical approaches. Table 1 shows the average K values obtained using the two techniques. From Table 1, it is evident that K values ranges from 1.18 x 10^{-5}cm/sec to 6.40 x 10^{-5} cm/sec.

The result of the t test (a=0.05), as summarized in Table 2, indicated that there is a slight difference in the geometric mean of the K values using the two techniques but the difference is not significant.This means that there is a 95% chance of the means not being significantly different. The implication of the t-test result is that we could still rely on the K values predicted using any of the two methods.Also, the correlation coefficients obtained between the two approaches is 0.9258; this signifies a strong positive linear correlation.

Table 1: Hydraulic Conductivities Results From the Two Approaches

| Sampling Locations in Southwestern Nigeria | Hydraulic Conductivities (cm/sec) | | | | | |
| | Geophysical Field Results | | | Geotechnical Results | | |
	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
Ile-Ife	2.38 x 10^{-5}	2.56 x 10^{-5}	2.71 x 10^{-5}	1.40 x 10^{-5}	2.81 x 10^{-5}	3.25 x 10^{-5}
Akure	1.06 x 10^{-5}	2.11 x 10^{-5}	1.85 x 10^{-5}	1.18 x 10^{-5}	1.48 x 10^{-5}	2.05 x 10^{-5}
Ibadan	2.37 x 10^{-5}	2.43 x 10^{-4}	2.26 x 10^{-5}	2.28 x 10^{-5}	2.52 x 10^{-5}	2.91 x 10^{-5}
Ondo	4.69 x 10^{-5}	3.74 x 10^{-5}	4.15 x 10^{-5}	1.99 x 10^{-5}	5.85 x 10^{-5}	5.85 x 10^{-5}
Ogbomoso	3.40 x 10^{-5}	4.29 x 10^{-4}	4.17 x 10^{-4}	1.20 x 10^{-5}	4.20 x 10^{-5}	5.71 x 10^{-4}
Ilesha	2.20 x 10^{-5}	2.38 x 10^{-5}	2.53 x 10^{-5}	1.84 x 10^{-5}	2.84 x 10^{-5}	3.44 x 10^{-5}

Table 2: Statistical T-Test Result of the Two Approaches Used in this Study

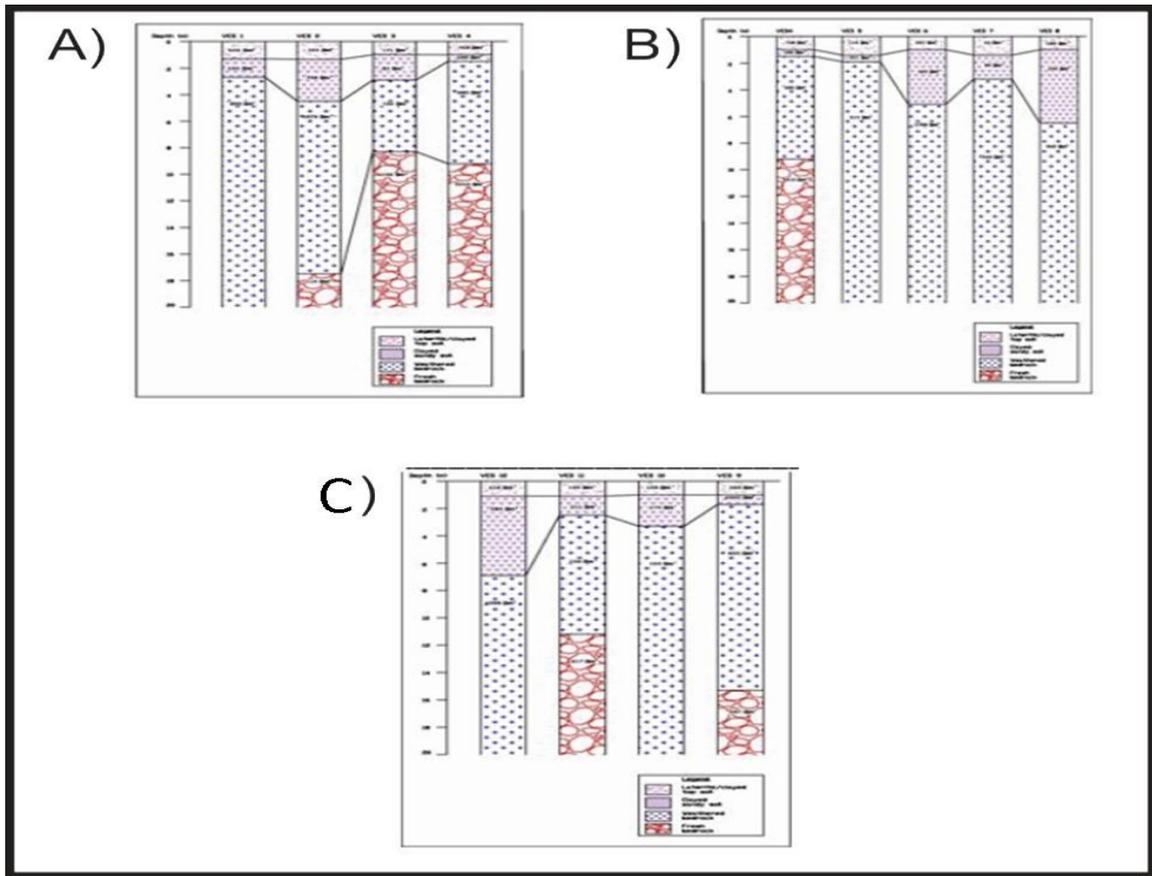| Data	Mean	Variance	N
K Values derived from Geophysical approach	0.0000829	1.79562E-8	18
K Values derived from Geotechnical approach	0.0000579	1.65901E-8	18
t-test	-0.57193		
P	0.57113		
Correlation coefficients (r)	0.92580		

Fig. 2: Geoelectrical Section along Traverses 1, 2 And 3
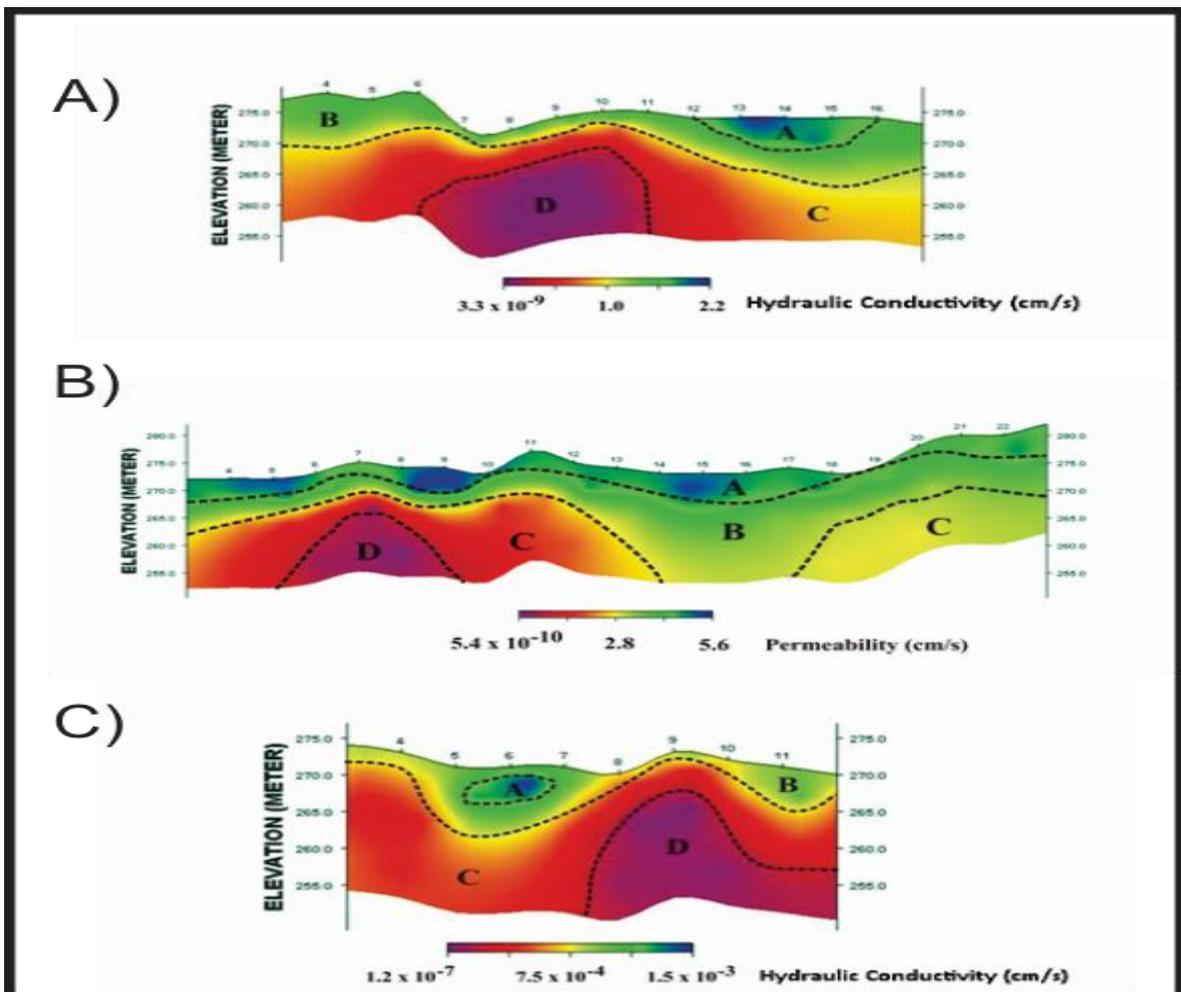

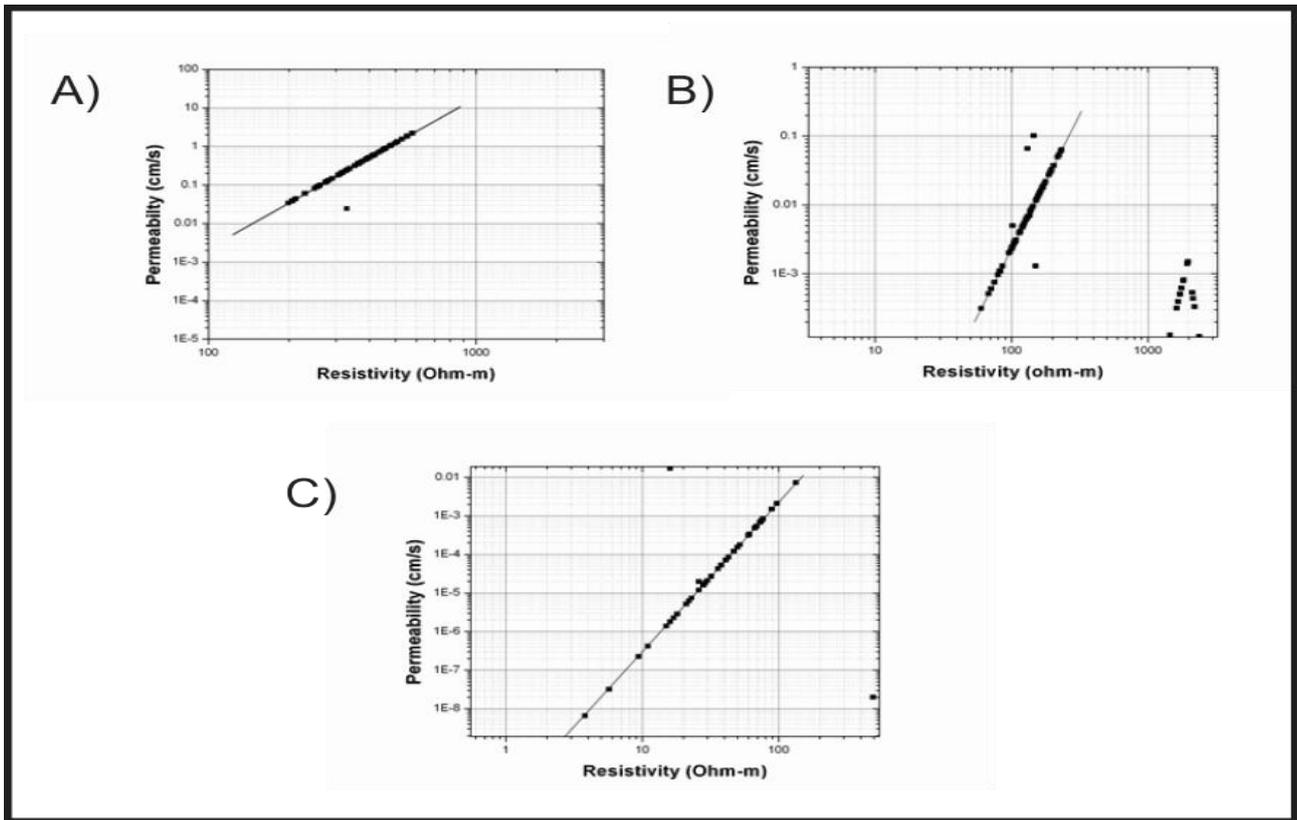**Fig. 3:** Hydraulic Conductivity Sections Obtained from Resistivity Data

Fig. 4: Permeability Vs. Resistivity Plot

Table 3: Summary of the Geotechnical Test Result for Ile-Ife

No	Test	Depth of collection 0.60m	1.20m	1.80m	2.40m	3.0m	Minimum Value	Maximum Value	Mean	Standard Deviation
1.	GRAIN SIZE ANALYSIS (%) Percent finer BS sieve 2mm Percent finer BS sieve 0.425mm Percent finer BS sieve 0.075mm	98.20 80.52 41.23	93.50 70.28 36.12	95.10 72.52 30.20	92.15 58.50 25.30	92.11 71.50 35.20	92.11 58.5 25.30	98.20 80.52 41.23	94.21 70.66 33.61	2.27 7.06 5.43
2.	NATURAL MOISTURE CONTENT (%)	15.5	10.8	22.8	24.5	18.5	10.8	24.5	18.42	4.95
3.	SPECIFIC GRAVITY	2.62	2.70	2.65	2.63	2.60	2.60	2.70	2.64	0.03
	ATTERBERG LIMIT (%) Liquid limit Plastic limit Plasticity Index Linear Shrinkage	38.5 21.06 17.44 4.32	34.0 11.4 22.6 5.12	37.0 16.3 20.7 5.78	37.5 24.0 13.5 6.50	43.0 38.5 24.5 5.50	34.0 11.4 13.5 4.32	43.0 38.5 24.5 6.50	38 22.25 19.75 5.44	2.92 9.18 3.90 0.72
5.	COMPACTION Maximum Dry Density (kg/m^3) Optimum Moisture Content (%)	1822 14.8	1720 15.0	1780 12.0	1880 14.0	1850 11.0	1720 11.0	1880 15.0	1810.40 13.36	55.93 1.59
6.	TRIAXIAL TEST Angle of internal friction ($^\circ$) Cohesion (kN/m^3)	32 28	36 21	34 24	20 22	24.5 27	20 21	36 28	29.3 24.4	6.06 2.73
7.	HYDRAULIC CONDUCTIVITY TEST Coeff. of Hydraulic. conductivity (cm/sec)	1.825×10^{-5}	2.215×10^{-5}	2.525×10^{-5}	2.452×10^{-5}	2.381×10^{-5}	1.825×10^{-5}	2.525×10^{-5}	2.28×10^{-5}	2.49×10^{-5}
8.	SOIL CLASSIFICATION Unified AASHTO Textural	SC A - 6 Sandy Clay loam	SC A - 6 Sandy Clay loam	SC A -2- 6 Sandy Clay loam	SC A -2- 6 Sandy Clay loam	SC A -7- 6 Sandy Clay loam				

4.4. Geotechnical test results

Typical results of the geotechnical engineering test carried out on soil samples obtained in the investigated area are shown in Table 3. From the entire test carried out, it is observed that the natural moisture content of the soils in all the pits sampled was found to have mean range of 15.64% to 20.97%. It is deduced that these values possibly depend on the climatic condition prevailing at the time of the sample collection. The specific gravity values obtained ranged from 2.47 to 2.73. Das (1990) showed that the specific gravity of clayey and silty soils vary from 2.6 to 2.9. The values obtained from this study falls within this range. Further, the average percentage of soil passing through sieves 2mm, 0.425mm and 0.075mm suggest that the grain sizes are between the sand and clayey soils range.

The average value of the liquid limit varies from 25.62% to 41.60% with mean value of 34.98%, while plastic limit varies from ranges from 12.71% to 27.60% with mean value of 20.35%.Also; the plasticity index varies from 12.72% to 19.75% with a mean value of 15.96% (See Table 3). The variation of plasticity index revealed that the soil samples are mainly inorganic clays of medium plasticity. The mean value of the linear shrinkage test varies from 4.77% to 8.90% with an average value of 6.33%. The shrinkage property of a soil is dependent on the clay content and this could be attributed to the nature of the soil samples mineralogy.

4.5. Soil classification

The soils analysed in study area were classified according to Unified Soil Classification System (Unified), AASHTO Classification system and Textural Classification system as shown in Table 3. According to the Unified classification system of the soil samples, 13.3% of the soil samples fall into CL group, which indicated that they are inorganic clays of low to medium plasticity.The remaining 86.7% fall into SC group which indicated clayey soils; poorly graded sandy clayey mixture or inorganic clays of medium plasticity. Using AASHTO soil classification, it is obvious that 63.4% of the soil samples fall into A-2-6 group, 3.3% into A-2-7, 13.3% into A-6 and 20% into A-7-6 groups respectively. A-2-6 and A-2-

7 groups have silty or clayey gravel and sand; while A-6 and A-7-6 have clayey soils in their own case. For Textural classification, 65% of the soil samples were classified as sandy clay soils while the remaining 34% are sandy clay loamy soils. It is pertinent to mention that these geotechnical test results agreed with the research findings of Olorunfemi and Okhue (1991) using geophysical approach.

4.6. Compaction and triaxial test

For the compaction test ,the maximum dry density (MDD) obtained varies from 1669.50 kg/m^3 to 1915.10 kg/m^3 with a mean value of 1834.75 kg/m^3.The corresponding optimum moisture content (OMC) of the soil samples in the study area ranges between 12.05% and 16.32% with a mean of 13.01%. All these values falls within the range known for lateritic soils found in the tropical region.

For the triaxial test conducted on the soil samples, it is evident that the values of the cohesion (c) vary from the minimum value of 21.40kN/m^2 to maximum value of 31.80kN/m^2 while the angle of internal friction is between 24 to 27 degrees (See Table 3). This confirm the cohesive nature of the soil arising from the clayey particles coupled with interlocking friction which is due to the sandy part of the soil samples.

4.7. Hydraulic conductivity test

Hydraulic conductivity (K) is a measure of the coefficient of soil permeability. Table 1 show the various values obtained for the pits dug in the six towns. Fig.5 shows the plot of the permeability against depth for all the pits sampled in this study. From the result, it is obviousthat the average K values vary from the minimum value of 1.18x 10^{-5} cm/sec to 2.28x 10^{-5} cm/sec. Our findings point to the fact that the typical values of the coefficients of hydraulic conductivity (K) of soils investigated in this study are within the range that could be defined as containing fine sand, silt and clay soils type as suggested by Das (1990).
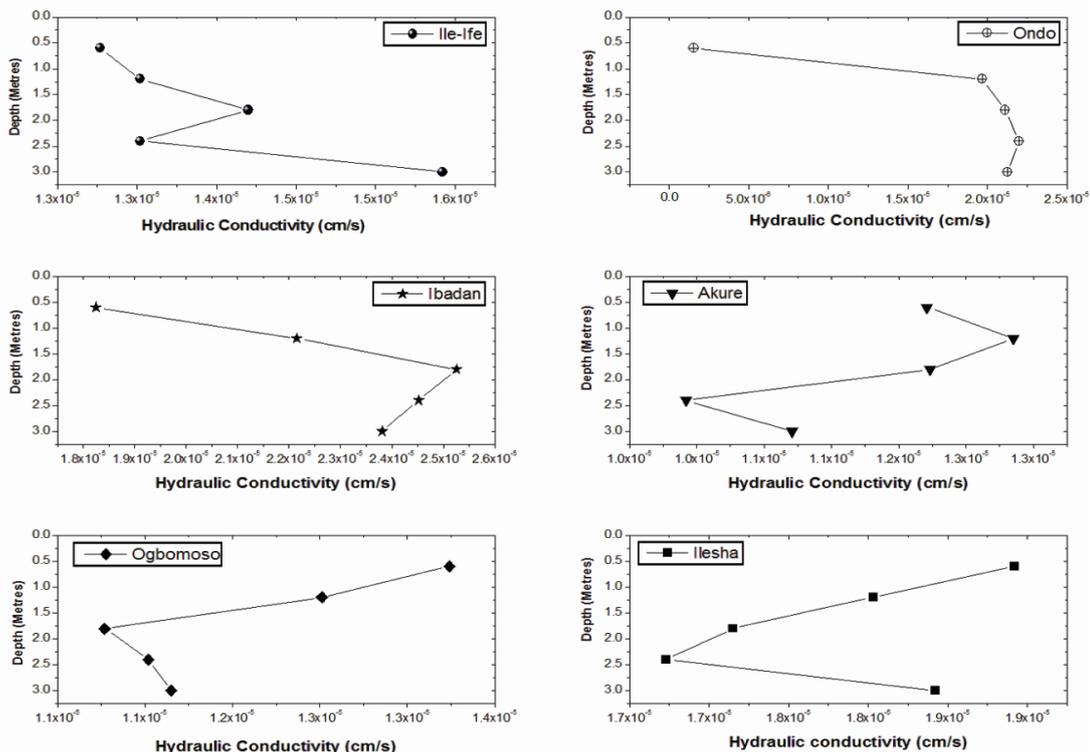

Fig. 5: Plot of Permeability against Depth

5. Conclusions

Integrated approaches have been applied in determining the hydraulic conductivities of lateritic soils found in the tropical region of southwestern Nigeria. Some of the existing buildings in the area frequently encountered groundwater seepage problem. Based on Unified soil classification system, it is revealed that the soils in the study can be grouped as mainly SC group which shows poorly graded sandy clayey mixture or inorganic clays of medium plasticity. The hydraulic conductivity (K) values obtained using geotechnical approach vary from 1.18×10^{-5} cm/sec to 5.71×10^{-4} cm/sec which still shows that it lies within the range of soils having relative permeability that is semi-pervious; on the other hand, geophysical method delineated four distinct and ubiquitous soil layers: lateritic topsoil, clayey-sand, sandy-clay layer and fractured and/or weathered bedrock. The K values obtained using geophysical approach ranges from 1.06×10^{-5} cm/sec to 4.29×10^{-4} cm/sec.

Also, the hydraulic conductivity values obtained from the two methods suggest the existence of moderate groundwater flow in some section of the project area. This may likely be responsible for the groundwater seepage noted. Furthermore, the t -test evaluation shows that at 95% confidence level, the results from both approaches are slightly different but strongly correlated. The reliability of using integrated approach for hydraulic parameter prediction and groundwater seepagemapping was confirmed from this study.

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