Development of Empirical Equations Relating Formation Resistivity and Cone Tip Resistance using Sedimentary and Basement Terrains of Nigeria as Case Studies.

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ABSTRACT

Vertical Electrical Sounding (VES) and Cone Penetrometer Test (CPT) results were used to investigate bridge/building sites in both sedimentary and basement terrains with a view to establishing empirical equations relating formation resistivity with cone penetrometer resistance. VES and CPT tests were carried out at five sites. The VES involved the Schlumberger array with electrode spacing (AB/2) varying from 1 to 100 m. The VES measurements were interpreted quantitatively using partial curve matching technique and 1-D Computer assisted forward modeling with WINRESIST software. The interpretation results were used to construct geo-electric sections. The cone penetrometer resistances were plotted with respect to depths and blocked into litho-units.

Both VES and CPT results were subsequently correlated. The plots of the formation resistivity values against averaged cone penetrometer resistances for both sedimentary and basement localities gave coefficients of correlation, for the linear and curvilinear regressions of 0.73 and 0.79 respectively. However, the plots of formation resistivity values against cone tip resistance for the sedimentary and basement environments separately on the semi-log and linear graphs gave correlation coefficients, for the sedimentary environment for linear and curvilinear regressions, of 0.9198 and 0.9192 respectively and for the basement environment correlation coefficients of 0.98 and 0.82 respectively. These higher values of correlation coefficients for each environment favor independent empirical equations for the different geologic environment.

This study concludes that a relationship exists between formation resistivity value and cone penetrometer resistance for sedimentary and basement environments. The generated empirical equations can be used in the field to transform formation resistivity value to cone tip resistance with a view to assessing the competence of rocks.

(Keywords: empirical equation, Schlumberger array, formation resistivity, cone penetrometer test, cone tip resistance, basement and sedimentary terrains)

INTRODUCTION

The electrical resistivity method is used in the study of horizontal and vertical discontinuities and in the detection of two and three dimensional bodies of anomalous electrical conductivities. The vertical electrical sounding (VES) technique measures vertical variations in apparent resistivity values with respect to a fixed centre of array by moving the current electrodes symmetrically from the potential electrodes (Telford et al., 1990). The VES data are interpreted in terms of subsurface layering and layer resistivity and thickness values. The formation resistivity increases with increase in the degree of compaction or competence and hence the resistance of such formation to cone penetration.

The Cone Penetrometer Test (CPT) is an *in situ* testing method used to determine the geotechnical engineering properties of soils and in the delineation of soil stratigraphy. The method involves pushing the Penetrometer cone into the soil while the resistance of the subsoil to penetration is continuously recorded with respect to depth. Three standard measurements are made and these include the tip resistance (q_c), sleeve friction (fs), and pore water pressure (u). Under certain circumstances, the tip resistance readings can be used to delineate soil stratigraphy and in testing natural sands, sandy fills and soils with deep water table (NCHRP Synthesis 368, 2007).

This study investigates empirically the relationship between formation resistivity estimated from the vertical electrical sounding data and cone penetration resistance in both sedimentary and basement terrains.

DESCRIPTION OF THE STUDY ENVIRONMENT

Five sites, located in both the sedimentary and basement terrains of Nigeria, were used as case study. The sites in the basement terrain include: Iboropa-Ise in Ondo State; Bali-Jamtari in Taraba State, and Gusau-Talata Mafara in Zamfara State. The two sites located in the sedimentary area include Gbagada in Lagos State and Asaka –Aboh in Delta State. Four of the five study locations are investigated bridge sites while only the Gbagada location is a building site.

The site locations, their geographic coordinates (Northings and Eastings in UTM) and accessibility are summarized in Table 1. Figure 1 is the map of Nigeria showing the study localities.

GEOLOGY OF THE STUDY AREA

Asaka-Aboh Road Bridge is underlain by the Quaternary Meander Belt deposit. The deposit is composed of sands, gravels and clays. It is located in the Niger Delta Basin. Gbagada locality is underlain by the Benin Formation of Dahomey Basin and comprises of alternations of sand and clay. Bali-Jamtari Road Bridge is underlain by Migmatite-Gneiss-Quartzite Complex of the basement terrain of Nigeria. The rocks comprise of Porphyritic Granite, Biotite Hornblende Granite and Migmatite Gneiss (Rahaman, 1988).

Table 1: Investigated Locations, Site Description and the Geographic Co-ordinates

SN	Locality	Site Description	Geographic Coordinates		Accessibility
			Northings (m)	Eastings (m)	
1	Gusau-Talata Mafara	Bridge 1 Bridge 2	210858 200899	1366420 1368514	Gusau-Talata Road, Zamfara State
2	Asaka-Aboh	Bridge 1	620472	222357	Asaka- Aboh Road
3	Bali-Jamtari	Lot 1 Bridge 1 Lot 2 Bridge 1 Lot 2 Bridge 3	865154 862918 862984	726347 741659 746624	Bali-Jamtari Road, Taraba State
4	Gbagada	Bridge 1	724078	541305	Gbagada across Ebinpejo Aromojobe Drainage channel, Lagos
5	Iboropa-Ise	Ise Bridge	821866	832092	Ugbe-Iboropa-Ise Akoko road, Ondo State

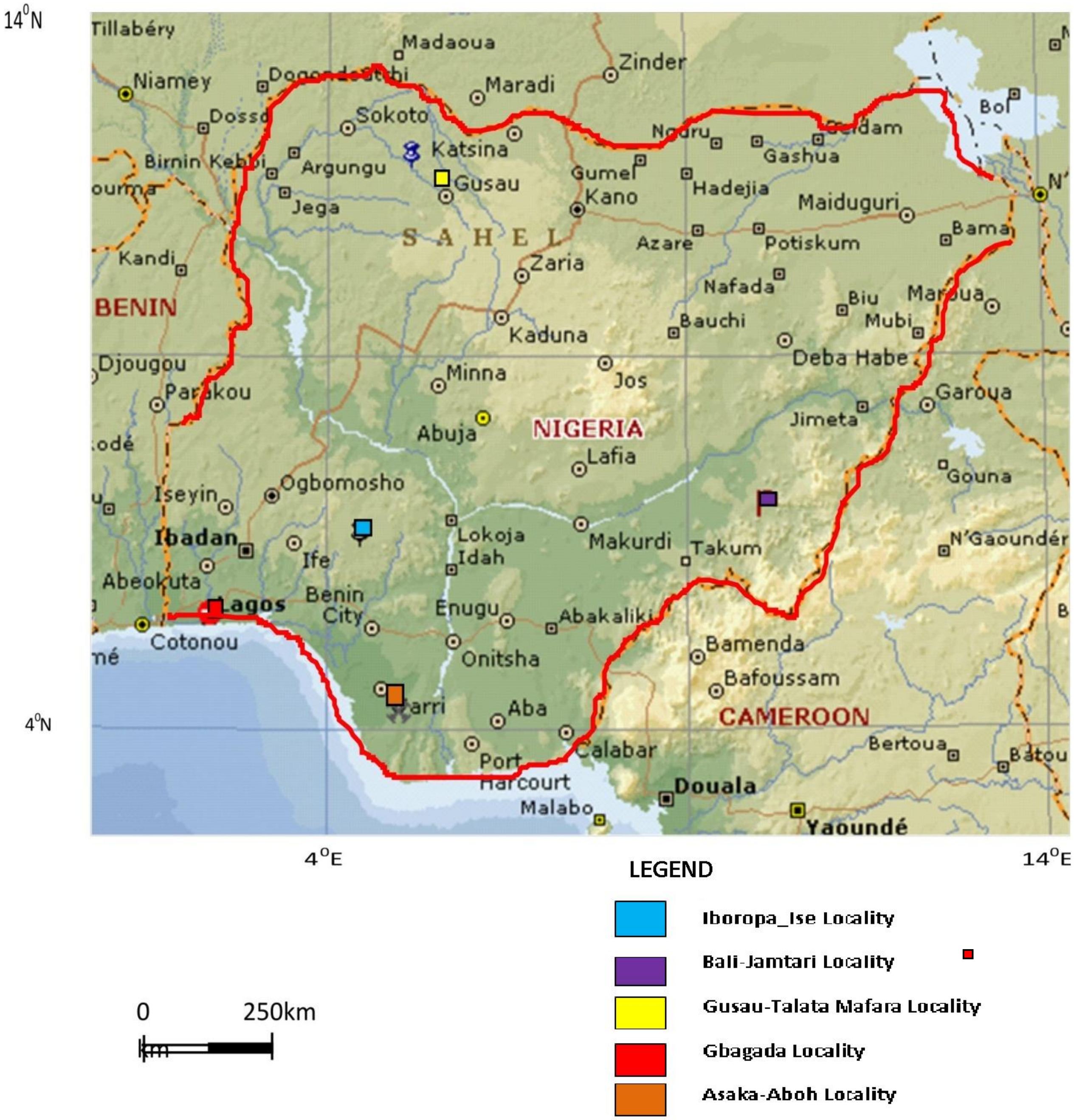


Figure 1: Map of Nigeria Showing the Study Areas (Adapted from Microsoft *Encarta*, 2009)

There are two proposed bridges along Gusau-Talata Mafara road. The proposed bridges are located on different rock types; bridge-one is sited on Schist while bridge-two is located on granite. The Iboropa-Ise Akoko Road Bridge is underlain by the Migmatite-Gneiss-Quartzite Complex of Nigeria. The rock type at the site of investigation is Migmatite Gneiss (Figure 2).

METHOD OF STUDY

Vertical electrical sounding (VES) technique and Cone Penetrometer Test (CPT) were used in both sedimentary and basement terrain of Nigeria. Several VES points were occupied at respective sites covering the proposed bridge abutments and the stream channel.

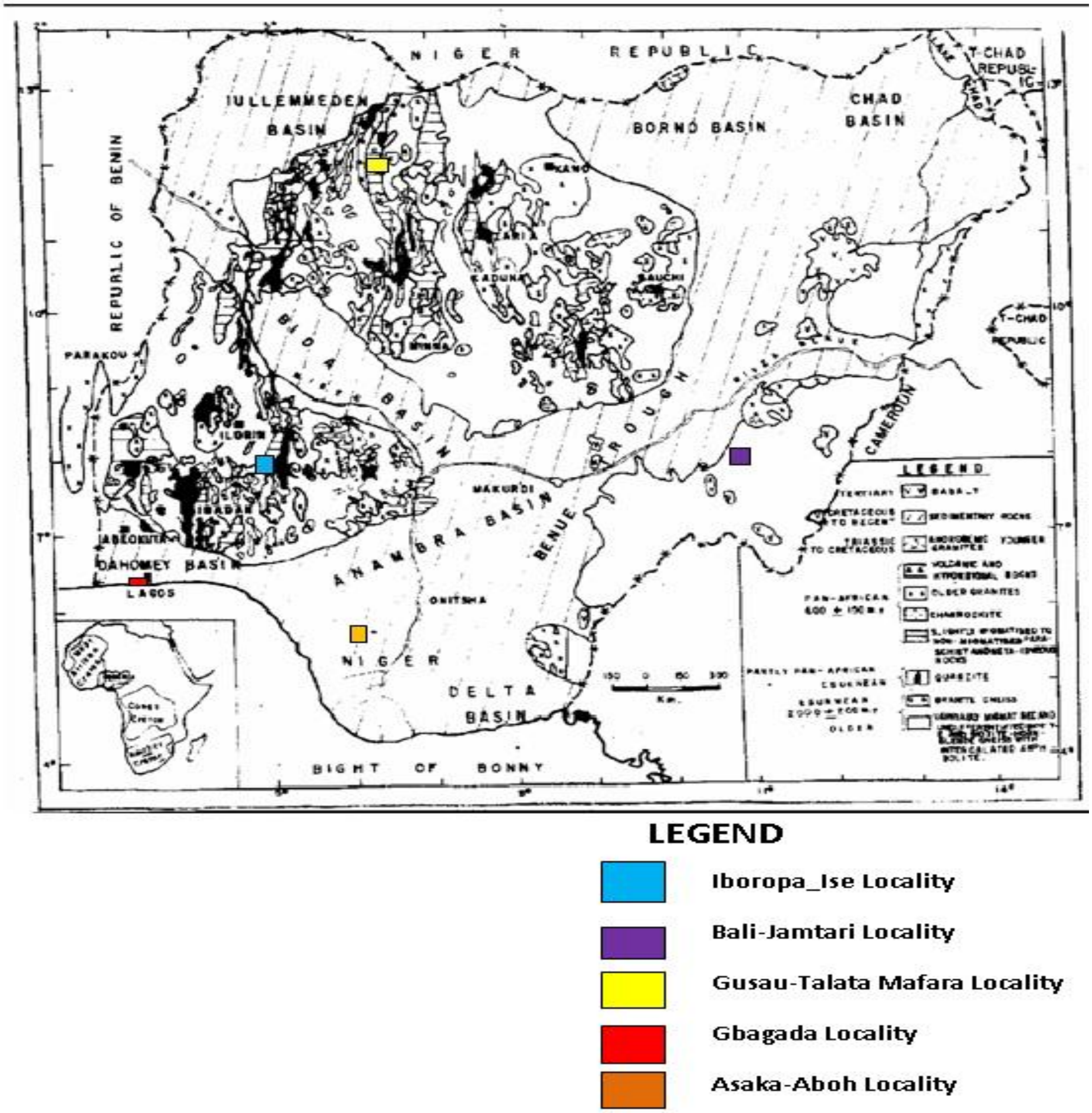
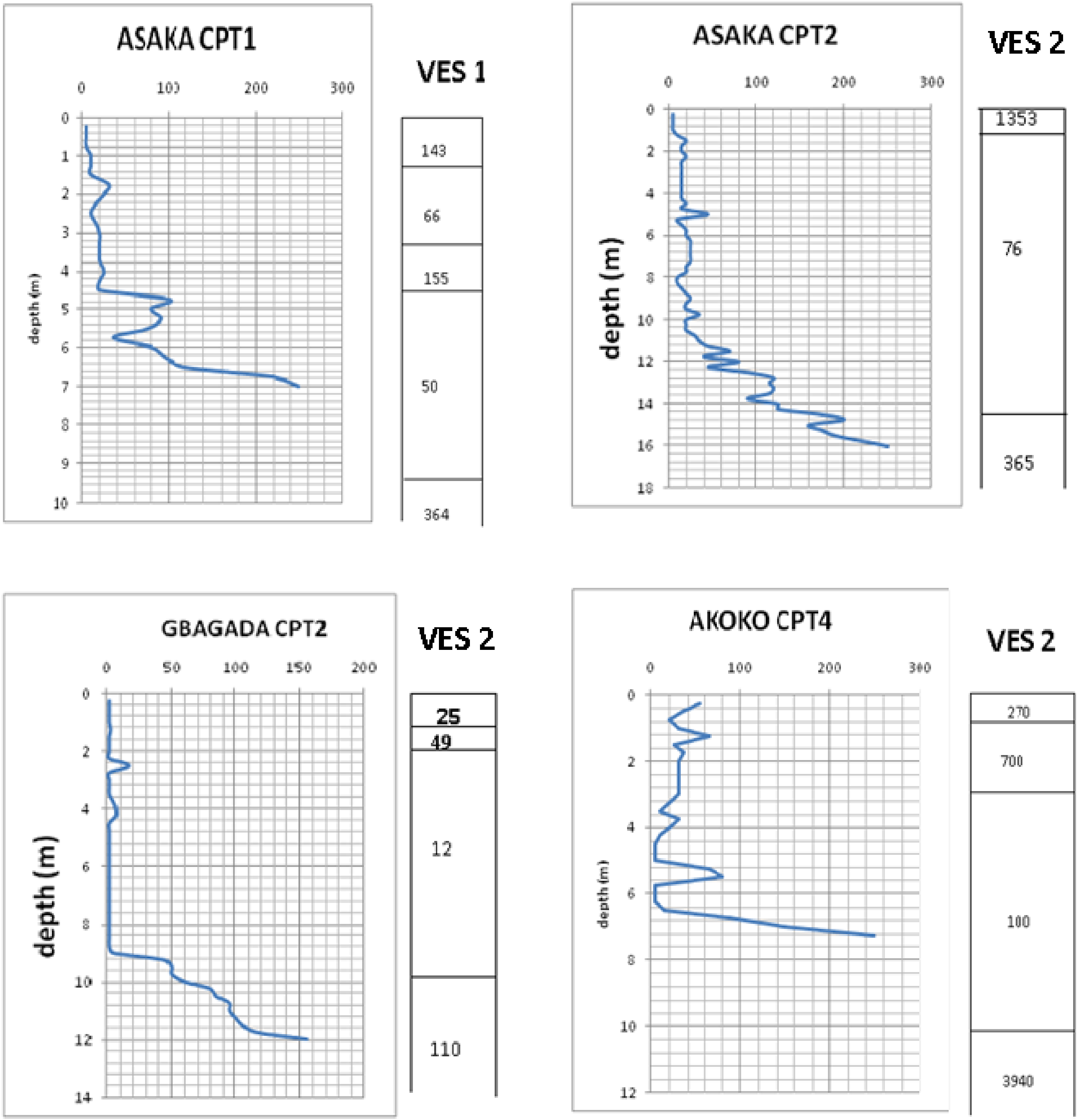


Figure 2: Generalized Geological Map of Nigeria (Adapted after Rahaman, 1988).

Both the VES measurement and the CPT measurements were taken at the same location. Schlumberger electrode configuration was used for the VES.

The vertical electrical sounding measurements were interpreted quantitatively using the partial curve matching technique and 1-D Computer assisted forward modeling with WINRESIST software. The interpreted results from the VES were used to construct geoelectric sections. The cone penetrometer resistances were plotted and blocked into litho-units. Both VES and CPT interpretation results were subsequently correlated (Figure 3).

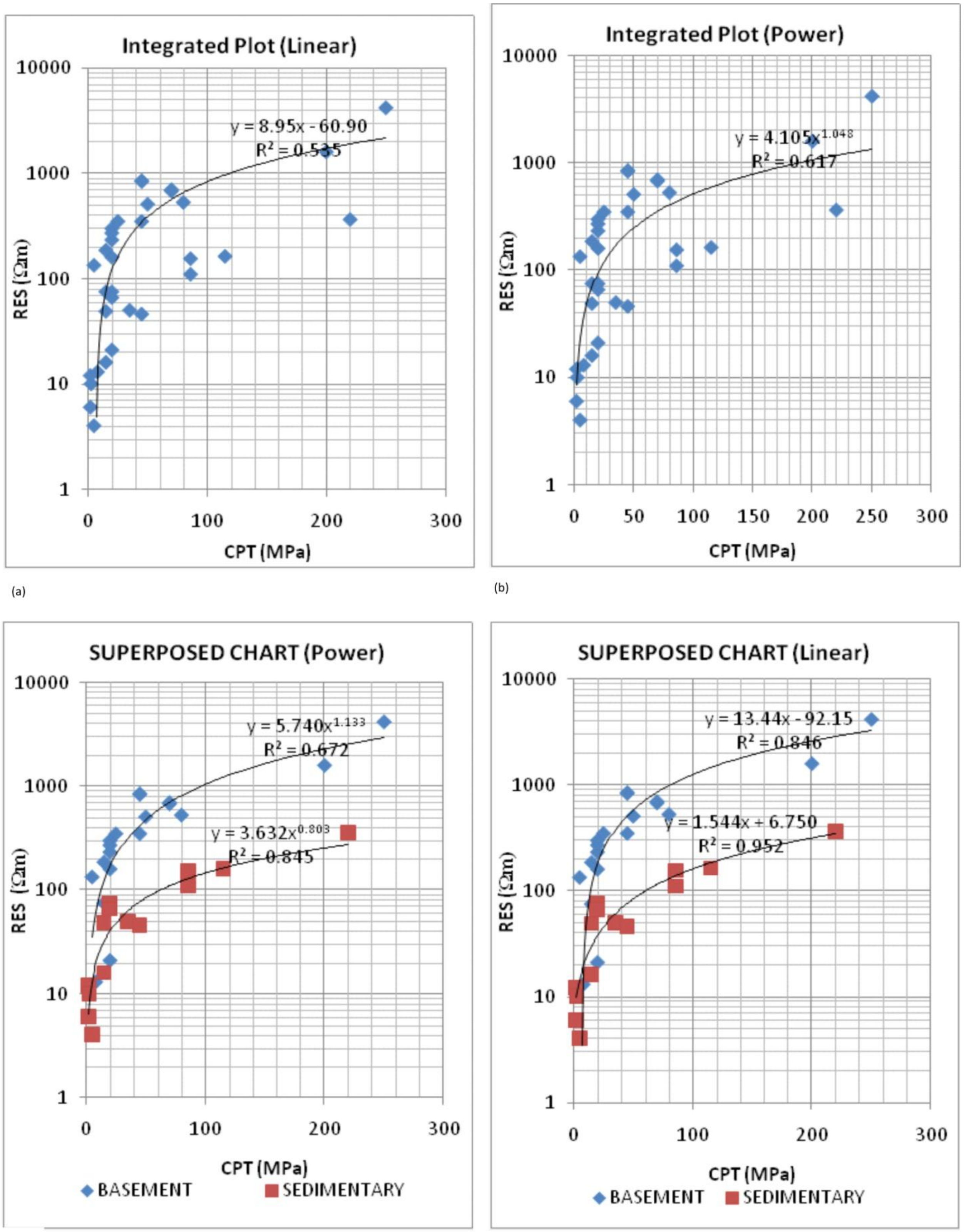


Values in the Geoelectric Sections are Resistivity Values (Ώm)

Figure 3: Typical Correlation of Observed CPT Curves with VES Interpretation Results.

RESULTS AND DISCUSSION

The plots of the VES derived formation resistivity values against cone penetrometer resistances for all the localities (sedimentary and basement) on semi-log graph paper (Figure 4a & b) show relatively low correlation coefficients of 0.73 and 0.79 for the linear and curvilinear regressions respectively. However, independent plots of formation resistivity values against cone tip resistance for the sedimentary and basement environments (Figure 4c & d) give correlation



(a)

(b)

(c)

(d)

Figure 4: Cross Plots of Formation Resistivity and Cone Tip Resistance (a) Integrated Plot (Linear), (b) Integrated Plot (Power), (c) Superposed Plots (Power), and (d) Superposed Plots (Linear).

coefficients for the sedimentary environment for linear and curvilinear regressions of 0.91978 and 0.9192 respectively and for the basement environment correlation coefficients of 0.98 and 0.82 respectively. These higher values of correlation coefficients favor independent empirical equations for the different geologic environment.

The generated empirical equations relating the formation resistivity with cone tip resistance are the following:

(i) Basement Environment:

RES = 13.44 * CPT – 92.15 --- (Linear Regression)

RES = 5.740 * ($CPT^{1.133}$) ---- (Curvilinear Regression)

(ii) Sedimentary Environment:

RES = 1.544 * CPT + 6.750 --- (Linear Regression)

RES = 3.632 * ($CPT^{0.803}$) ---- (Curvilinear Regression)

where; RES represents formation resistivity values in Ώm and CPT represents cone tip resistance in KgF/cm^2.

The generated empirical equations were tested on the sedimentary and basement environments using results from the investigated sites. The empirical equations were used to derive pseudo-cone tip resistance curve at each VES station. The pseudo-CPT results obtained from the linear and curvilinear regression equations were superimposed on plot of the CPT results for each locality (Figure 5).

Figures 5a-f show significant correlation between observed CPTs and computed pseudo-CPTs generated from the linear and curvilinear regression equations for both geologic environments. However, the pseudo-CPTs identify, within the sedimentary environment, near-surface high resistivity loose sands which display low observed cone tip resistances.

At some of the sites (e.g. Asaka CPT1, Bali Lot 2, Brid 3 and Akoko CPT4), the Penetrometer derived competent bedrock (the interface of refusal) may have been precipitated by boulders or hard pan since the true competent bedrock interfaces are, judging by the VES interpretation results, at deeper depths (see Figure 5 a, e & f).

This is one of the limitations of the Cone Penetrometer Test that this study has highlighted, in addition to its relatively shallow depth of investigation when compared with the VES technique.

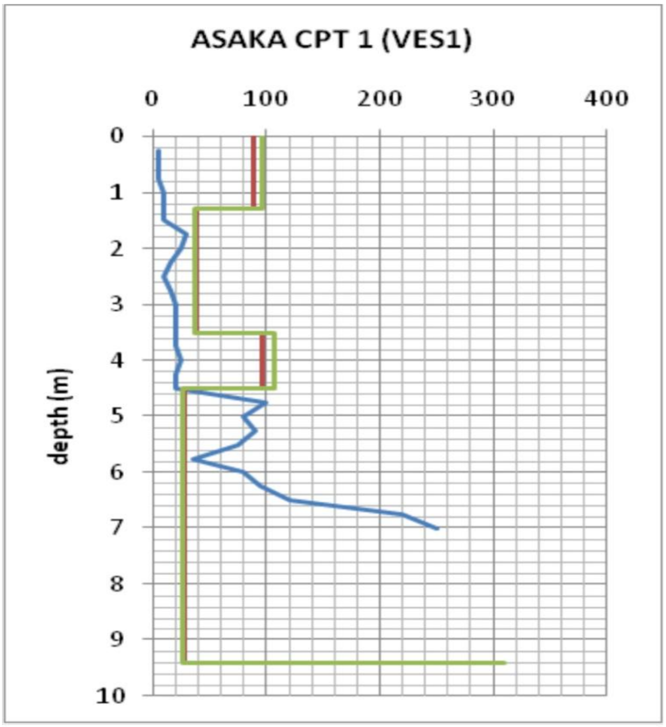
Limitations of the Empirical Equations

The generated empirical equations have limitations in areas where there is saline water intrusion and the subsurface rock is saline. Salinity leads to reduction in formation resistivity which will result in underestimation of the cone tip resistance. Hydrocarbon impacted soils become abnormally resistive. This will result in abnormally high estimated cone tip resistance and hence the degree of competence.

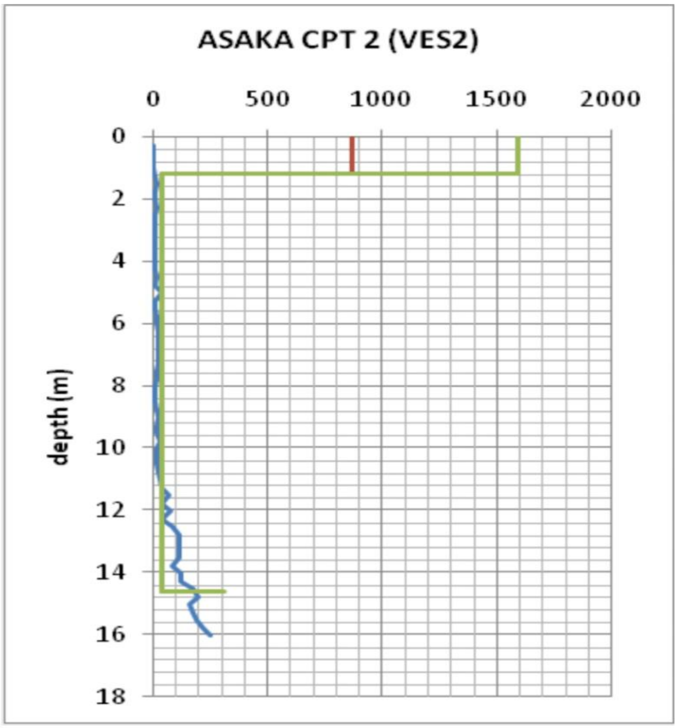
CONCLUSION

Vertical Electrical Sounding (VES) and Cone Penetrometer Test (CPT) were used to investigate bridge and/or building sites in both sedimentary and basement terrains for subsurface sequence delineation and competence assessment. The plots of formation resistivity values against cone penetrometer resistances for all the localities (sedimentary and basement) on semi-log graph give relatively low correlation coefficients of 0.73 and 0.79 for the linear and curvilinear regressions respectively. However, independent plots of formation resistivity values against cone tip resistance for the sedimentary and basement environments give correlation coefficients for the sedimentary environment for linear and curvilinear regressions of 0.91978 and 0.9192, respectively, and for the basement environment correlation coefficient of 0.98 and 0.82 respectively.

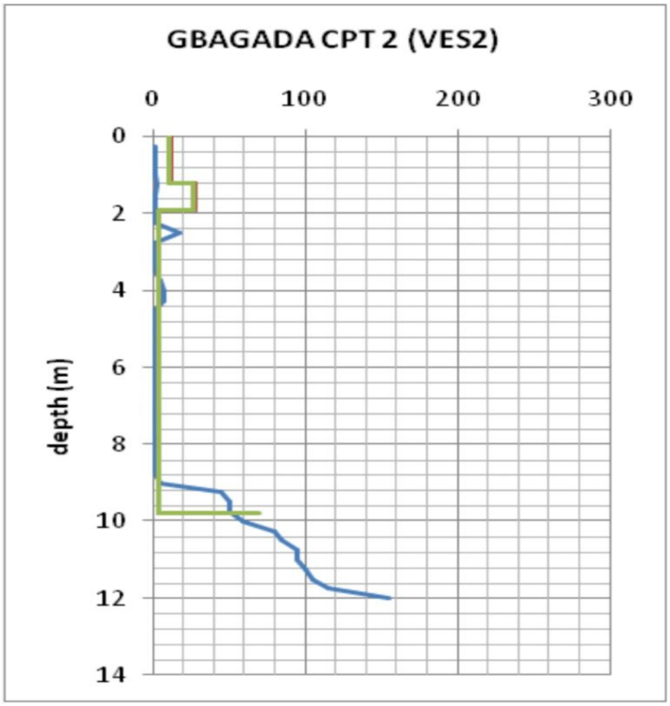
These higher values of correlation coefficients favor independent empirical equations for the different geologic environment. Such empirical equations can be relevant in engineering site investigation for the assessment of competence of subsurface rocks.


ASAKA CPT 1 (VES1)
0
100
200
300
400
depth (m)
0
1
2
3
4
5
6
7
8
9
10

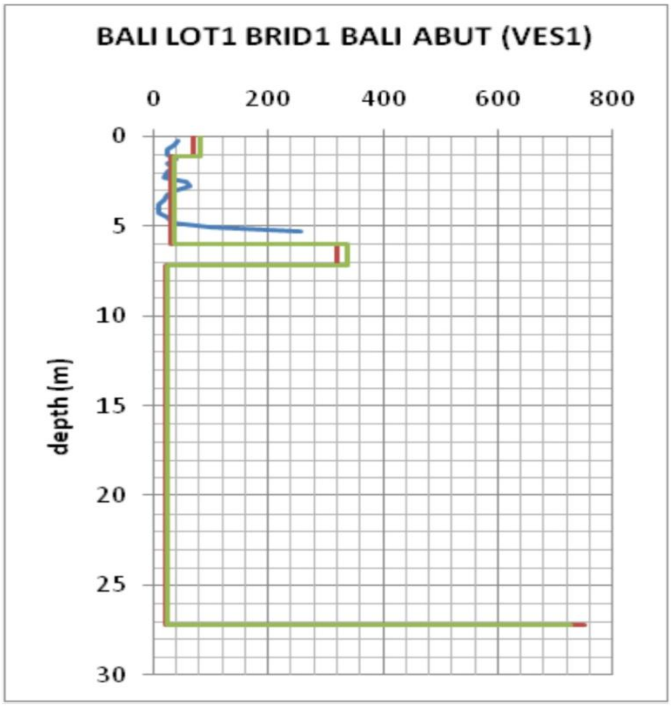
(a)


ASAKA CPT 2 (VES2)
0
500
1000
1500
2000
depth (m)
0
2
4
6
8
10
12
14
16
18

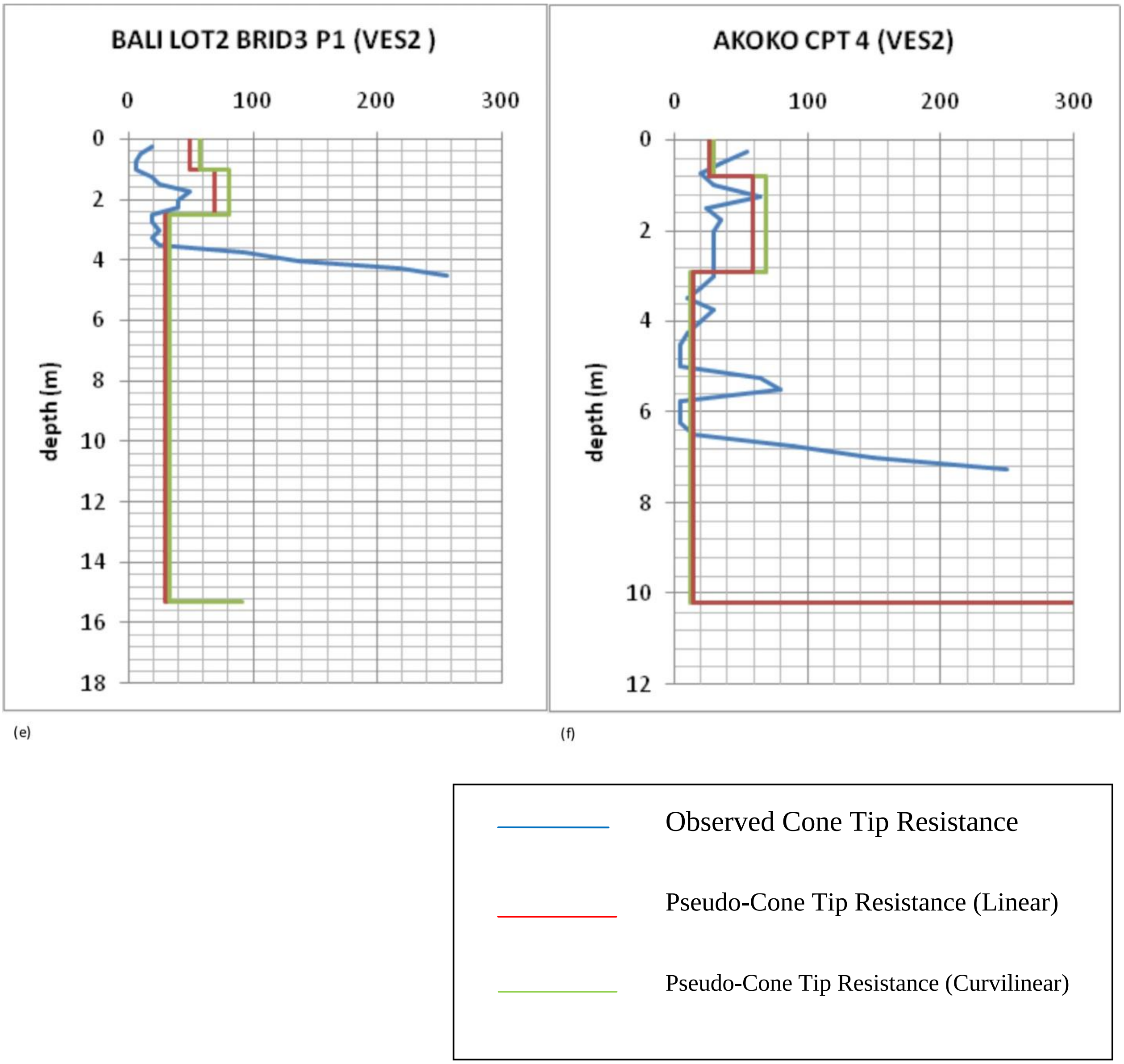
(b)


GBAGADA CPT 2 (VES2)
0
100
200
300
depth (m)
0
2
4
6
8
10
12
14

(c)


BALI LOT1 BRID1 BALI ABUT (VES1)
0
200
400
600
800
depth (m)
0
5
10
15
20
25
30

(d)



(e)

(f)

Figure 5: Correlation of Cone Tip Resistance and Pseudo-CPT Results (a) Asaka CPT 1 (VES 1); (b) Asaka CPT 2 (VES 2); (c) Gbagada CPT 2 (VES 2); and (d) Bali Lot 1 Bridge 1 Bali Abutment (VES 1). Results (e) Bali Lot 2 Bridge 3 P1 (VES 2) and (f) Akoko CPT 4 (VES 2).

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