IOP Publishing Journal of Geophysics and Engineering
J. Geophys. Eng. 14 (2017) 675–690 (16pp) https://doi.org/10.1088/1742-2140/aa64f7

Foundation integrity assessment using integrated geophysical and geotechnical techniques: case study in crystalline basement complex, southwestern Nigeria

G M Olayanju[1], **K A Mogaji**[1,2,3], **H S Lim**[2] **and T S Ojo**[1]

[1] Department of Applied Geophysics, Federal University of Technology, P.M.B. 704, Akure, Nigeria
[2] School of Physics, Universiti Sains Malaysia, 11800 Penang, Malaysia

E-mail: gmolayanju@gmail.com, mogajikehindeantony@gmail.com, hslim@usm.my and OJOSAM@gmail.com

Received 26 May 2016, revised 5 March 2017
Accepted for publication 7 March 2017
Published 27 April 2017

Abstract

The determination of parameters comprising exact depth to bedrock and its lithological type, lateral changes in lithology, and detection of fractures, cracks, or faults are essential to designing formidable foundations and assessing the integrity of civil engineering structures. In this study, soil and site characterization in a typical hard rock geologic terrain in southwestern Nigeria were carried out employing integrated geophysical and geotechnical techniques to address tragedies in civil engineering infrastructural development. The deployed geophysical measurements involved running both very low frequency electromagnetic (VLF-EM) and electrical resistivity methods (dipole–dipole imaging and vertical electrical sounding (VES) techniques) along the established traverses, while the latter technique entailed conducting geological laboratory sieve analysis and Atterberg limit-index tests upon the collected soil samples in the area. The results of the geophysical measurement, based on the interpreted VLF-EM and dipole–dipole data, revealed conductive zones and linear features interpreted as fractures/faults which endanger the foundations of public infrastructures. The delineation of four distinct geoelectric layers in the area—comprised of topsoil, lateritic/clayey substratum, weathered layer, and bedrock—were based on the VES results. Strong evidence, including high degree of decomposition and fracturing of underlying bedrock revealed by the VES results, confirmed the VLF-EM and dipole–dipole results. Furthermore, values in the range of 74.2%–77.8%, 55%–62.5%, 23.4%–24.5%, 7.7%–8.2%, 19.5%–22.4%, and 31.65%–38.25% were obtained for these geotechnical parameters viz soil percentage passing 0.075 mm sieve size, liquid limit, plasticity index, linear shrinkage, natural moisture content, and plastic limit, respectively, resulting from the geotechnical analysis of the soil samples. The comparatively analyzed geophysical and geotechnical results revealed a high weathering of charnockitic rocks resulting in plastic clay material mapped with a mean resistivity value of 73 Ohm-m, in conformity with the obtained geotechnical parameters, which failed to agree with the standard specification of subsoil foundation materials and which, in turn, can impact negatively on the foundational integrity of infrastructures. Based on these results, the area subsoils' competence for foundation has been rated poor to low. This study has more widely demonstrated the effective application of integrative geophysical and geotechnical methods in the assessment of subsoil competence.

[3] Author to whom any correspondence should be addressed.

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

 © 2017 Sinopec Geophysical Research Institute Printed in the UK

Keywords: geophysical, foundation integrity, geoelectric layers, geotechnical parameters, soil competence, public infrastructures

(Some figures may appear in colour only in the online journal)

1. Introduction

The application of pre-foundational studies is becoming more important nowadays, in light of the current spate of collapsing civil engineering structures such as building, roads, and dams across developing countries like Nigeria (Akintorinwa and Adeusi 2009, Oyedele *et al* 2011, Coker 2014). In accordance with Adelusi *et al* (2013), these structural failures are often attributed to problems of substandard usage of building materials, old age of buildings, and improper foundation design. However, other vital causes discovered to be undetected near surface structures such as cavities, sinkholes, and faults associated with the properties of earth-founded materials are often trivialized by foundation designers and structural engineers prior to infrastructure development and construction (Parolai *et al* 2001, 2002, Delgado *et al* 2002, Lebourg *et al* 2003, 2005, Fatoba *et al* 2010, Adeyemo *et al* 2014). The impacts of the above-mentioned structural failures are enormous, including loss of life and valuable property among several others (Arosio *et al* 2013, Coker 2014, Adejumo *et al* 2015, Longoni *et al* 2016). As such, the need arises for proper subsurface soil evaluation with a view of providing the earth subsurface information necessary for the proper design of formidable civil engineering structures. In accordance with Bowles (1984) and Adeyemo and Omosuyi (2012), foundation design, being a typical civil engineering infrastructure, requires the proper determination of depth to subsurface bedrock, its geotechnical integrity as well as an evaluation of its physical properties. The classic foundation types usable in the erection of civil engineering structures include both shallow and deep footing. The appropriateness of these foundation types to building infrastructure, including low- and high-rising buildings, largely depend on the subsoil geotechnical parameters characterizing varying lithological layers at depth. Thus, the potential of geophysical and geotechnical techniques in mapping and evaluating subsurface formations and physical/engineering properties are investigated with a view towards the future design of good foundations that can address the incessant structural tragedies peculiar to engineering infrastructural development.

Engineering geophysics is the aspect of geophysics that deals with studying the Earth's subsurface information, including the physical properties of the surrounding area, for the proper design of civil engineering structures (Sharma 1997, Lebourg *et al* 2003, Soupios *et al* 2007, Ofomola *et al* 2009, Longoni *et al* 2014). According to Adeoti *et al* (2016), Kayode *et al* (2016), and Mogaji (2016), geophysics is a non-destructive, cost effective, and very reliable means of imaging the Earth's subsurface. Consequently, several geophysical prospecting methods have been employed in a wide range of applications, ranging from building ground investigations to the inspection of dams and dikes for the purpose of imaging subsurface geological structures and determining the physical parameters of the rock formations (Luna and Jadi 2000, Venkateswara *et al* 2004, Othman 2005, Soupios *et al* 2006). The most often used geophysical techniques, particularly in engineering studies, include electrical resistivity (Griffiths and Arker 1993, Lebourg and Frappa 2001, Seaton and Dean 2004, Rubin and Hubbard 2005), very low frequency electromagnetic (Sharma and Barawal 2005), magnetic (Sultan and Santos 2009), and seismic refraction methods (Jongmans *et al* 2000, Sumanovac and Weisser 2001, Lebourg *et al* 2003, Socco and Strobbia 2004, Sundarajian *et al* 2004, Lebourg *et al* 2005, Socco *et al* 2010). With the application of these geophysical techniques, scientific results and the need to reinforce certain soil materials in order to enhance their bearing capacities (and thus the lifespan of any proposed engineering structures) have been established. By applying these techniques, moreover, the delineation of subsurface geomorphological configuration (ridges and depression zones) and mapping of basement geological structural features (faults, joint/fissures) that can be inimical to engineering foundation structures have been reported (Ayodele 2009, Ofomola *et al* 2009, Adeyemo *et al* 2014). Thus, these techniques are more widely explored for foundational integrity assessment viz-a-viz providing either 2D or 3D images of the subsurface that can be used to identify areas that can pose a threat to future building foundations or cause future building collapses.

Geotechnical study is another investigation approach that can provide excellent insight into the engineering properties of the subsurface soil materials (Holtz and Kovacs 1981, Woodward 2005, Olayanju 2011a). The understanding of soil properties in particular is of the utmost importance in foundation study because it gives insights into the material properties of the soils, including whether they can support the load often exerted by the type of structure to be built. Therefore, in determining and designing the type of foundations, earthworks, and/or pavement subgrades required for the man-made structure to be built, geotechnical study has been widely explored (Giao *et al* 2000a, 2000b, Tanaka *et al* 2001, Chung *et al* 2002, Giao *et al* 2002). Information from this technique, such as the geotechnical and engineering properties of the soil materials essential to the design of the foundation, can be evaluated.

The combination of measurements from the just-discussed geophysical and geotechnical techniques, in accordance with Soupios *et al* (2007), can greatly improve building quality by revealing both laterally and vertically the subsurface geology for possible accurate environmental decision making. This is quite necessary given the proficiency of the applied geophysical methods in assessing subsoil integrity as applicable to dams and foundations (Holtz and Kovacs 1981, Sumanovac and Weisser 2001, Adelusi *et al* 2013, Adeoti *et al* 2016), as well as the effectiveness of geotechnical technique in adequately defining subsurface conditions through determination of the *in situ* bulk properties of soil and

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

rock underlying an area (Anderson *et al* 2008). The integrated application of these techniques in a typical crystalline basement complex terrain will largely provide accurate mapping of subsoil as a foundation material, with implications for foundation competency evaluation.

Exploring the combined applications of geophysical prospecting techniques and geotechnical soil analyses, as well as measurement in a typical crystalline basement complex with a view to ascertaining the suitability of subsoil as foundation material and the resulting implications on foundation competency evaluation, is attempted in this study. The paper thus provides a cost-effective way to assess the competence and integrity of subsoil as a material for the construction of civil engineering structures, as well as obtain an understanding of the geologic nature of the environment at the planning stage of infrastructure development. Moreover, insights into the likely basic problems of subsurface structural features that could be inimical to civil engineering structures can be revealed and remediation actions recommended.

2. Study area description

The study area is a site for a proposed private college located close to an industrial estate situated within the Akure metropolis in the southwestern part of Nigeria. The area geology, according to Rahaman (1988), is of that of precambrian crystalline basement complex rocks of southwestern Nigeria. The localized lithologic unit is primarily monolithic, typical of charnockitic rock, with sparse occurrences of low-lying outcrop of migmatite-gneiss at the southwestern part of the study area (figure 1(a)). It is important to note that some preserved traits of deformation in the charnockitic rocks of the Akure area have been reported by Ademeso (2009), while the field and petrographic relationships between the charnockitic and the associated granitic rocks of the area have also been reported by Ademeso (2010). The fine-grained rock in this study area is believed to have originated from charnockitic magma that has been contaminated substantially by the pre-existing porphyritic granite; therefore, it will be more appropriate to refer to it as a hybrid (Ademeso and Alabi 2011). The authors have concluded that the charnockitic rocks were younger than the granitic rocks of the Pan-African age and of igneous origin. The earmarked site, as identified on the geological map, lies within latitudes 07° 16′ 33″ N to 07° 16′ 38″ N and longitudes 05° 09′ 58″ E to 05° 10′ 04″ E (figure 1(b)).

3. Materials and methods

Geophysical and geotechnical methods were employed for assessing the competency and suitability of the area subsoil as foundation material in the proposed private college prior to the infrastructural development. Six geophysical traverses, in the range of 65 to 100 m long, were established along the SW–NE and NW–SE directions on the investigated site (figure 1(b)). On the established traverses are the located soil sample points obtained for the geotechnical laboratory analysis. Very low frequency electromagnetic (VLF-EM) and electrical resistivity (ER) techniques were deployed for geophysical measurements along the traverses (figure 1(b)). The geophysical investigation constituted the first phase of the study. Using ABEM-WADI equipment manufactured by the ABEM Corporation, Sweden, the VLF-EM measurement was conducted along the traverses oriented from SW–NE. For this equipment measurement and recording, the transmitter location is at the NAU station, Aguada, Puerto Rico, with transmission frequency of 27.5 kHz and signal strength of 13.6 dB. The traverse orientation is approximately 058° NW and the transmitter azimuth is 082° NW. On each of these traverses, the real (in-phase) and imaginary (quadrature) components of the induced vertical magnetic field were observed with station intervals of 5 m and were expressed as a percentage of the horizontal primary field.

The processing of the measured real (in-phase) and imaginary (quadrature) values yielded the VLF-EM profiles and their tomographic 2D imaging current density sections, inverted using the KHFilt™ inversion software (Karous and Hjelt 1983), as presented in figures 2(a)–(d). In accordance with Olayanju (2011b), the combined interpretation of the raw real EM profiles and their filtered components with the 2D imaging current density sections that were produced greatly aid the evaluation of the subsurface geology of the site in terms of visual inspection for conductive anomalies (characteristic weak zones) that are diagnostic of subsurface geological structures overlying or within the bedrock. However, in order to have a better imaging of the subsurface structures at deeper depth (considering the soil resistivity variation both in the lateral and vertical direction within the area) the dipole–dipole imaging technique of the ER method was also adopted (Griffiths and Arker 1993, Robain *et al* 1996, Ritz *et al* 1999). The dipole–dipole ER data were obtained using inter-electrode spacing of 2 m, and inter-dipole expansion factor (n) varied between 1 and 5. Employing the DIPPROTM inversion software (Dipro for Windows 2001), the quantitative inversion of the dipole–dipole data was conducted to produce 2D subsurface images or resistivity structures.

Based on the VLF-EM and dipole–dipole ER data, the vertical electrical sounding (VES) points were selected. With the use of an Ohmega resistivity meter and the employed Schlumberger array, adopting electrode spread in the range of 2 to 135 m, a total of 16 sounding stations were occupied on the traverses (figure 1(b)). The obtained model geoelectric parameters for the delineated layers were based on the determined initial layer parameters obtained from the manual curve-matching interpretation of the field-generated resistivity curves, which were further iterated using the WIN RESIST software (Vander Velper 2004).

The results obtained from the interpretation of the combined geophysical data served as a guide for selecting the location of soil samples used for the geotechnical analyses.

The second phase of this study involved geotechnical laboratory tests of five undisturbed soil samples collected using a soil auger at different locations at a depth of 1 m within the site and labeled samples A–E (figure 1(b)). The

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

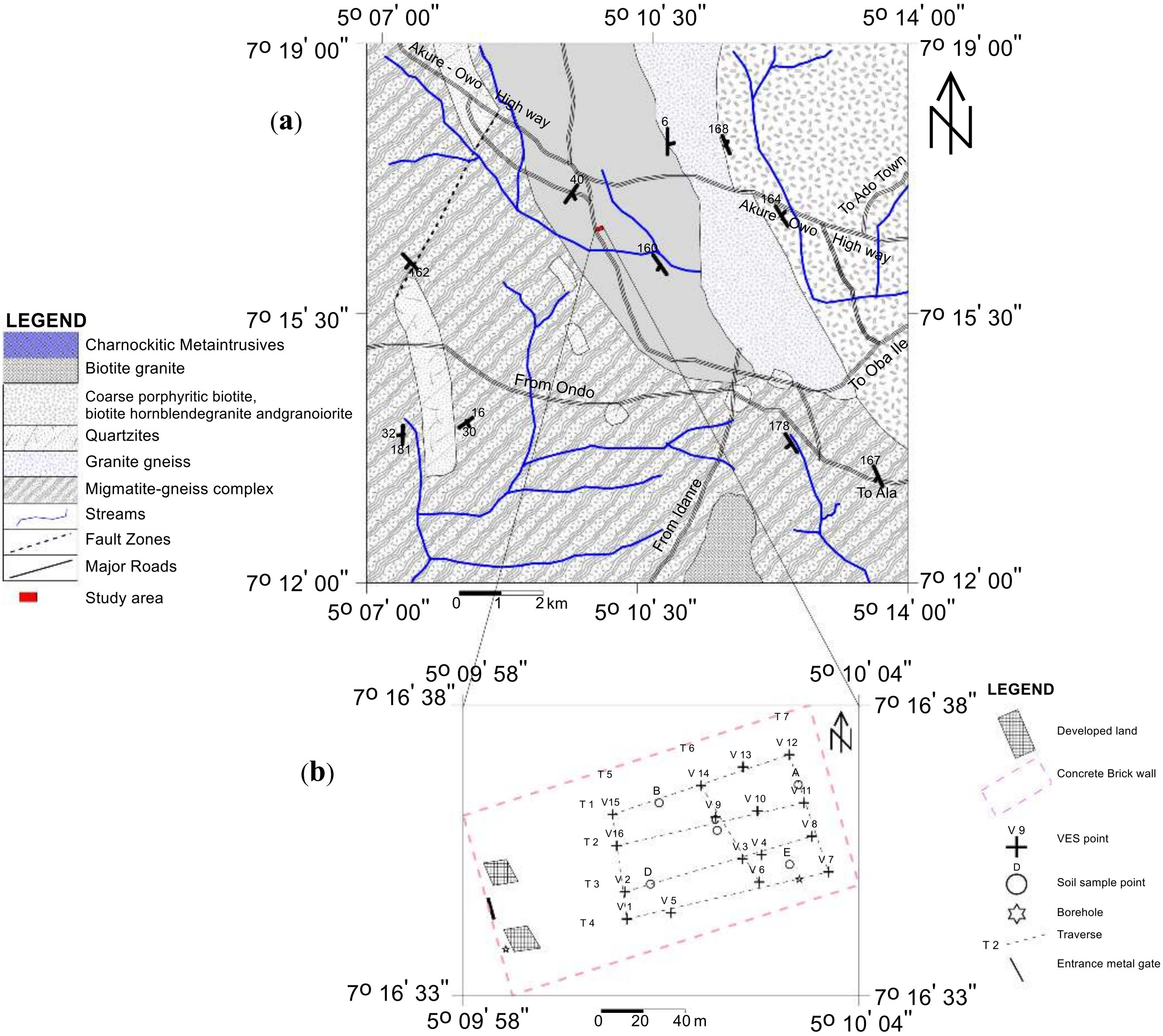

Figure 1. Location maps showing (a) the geological map of Akure, southwest Nigeria, and (b) the site map of the study area displaying the data-acquisition traverses.

geotechnical tests conducted on the samples included determination of clay content through grain size analysis, Atterberg limits test, and hydrometer analysis (Das 1998, Santamarina *et al* 2001). These tests were conducted in accordance with B.S. 1377 geotechnical analyses guides. The natural moisture content of each of the soil samples was also determined.

4. Results and discussion

4.1. VLF-EM data model results

Figures 2(a)–(d) show diagnostic models of the subsurface geology from the interpreted VLF-EM data acquired along four traverses (T1–T4) in the study area. The output 2D models from the inverted VLF-EM current density sections show the variation in the computed apparent current density of one or more layers whose depth of investigation largely depends on the orientation, operating frequency of the instrument, and conductivity of individual lithologic layers. With such inverted current density sections (figures 2(a)–(d)) produced, the qualitative discrimination between the conductive and resistive structures were mapped (Benson *et al* 1997, Olayanju 2011b). However, it is important to note that the acquired VLF-EM field data were smeared by the strong influence of fence, resulting in the weak EM signals observed in the data towards the ends of the profiles (figures 2(a)–(d)). This is one of the pitfalls attributed to strong cultural noise from man-made structures, which culminated in the attenuation of the observed

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

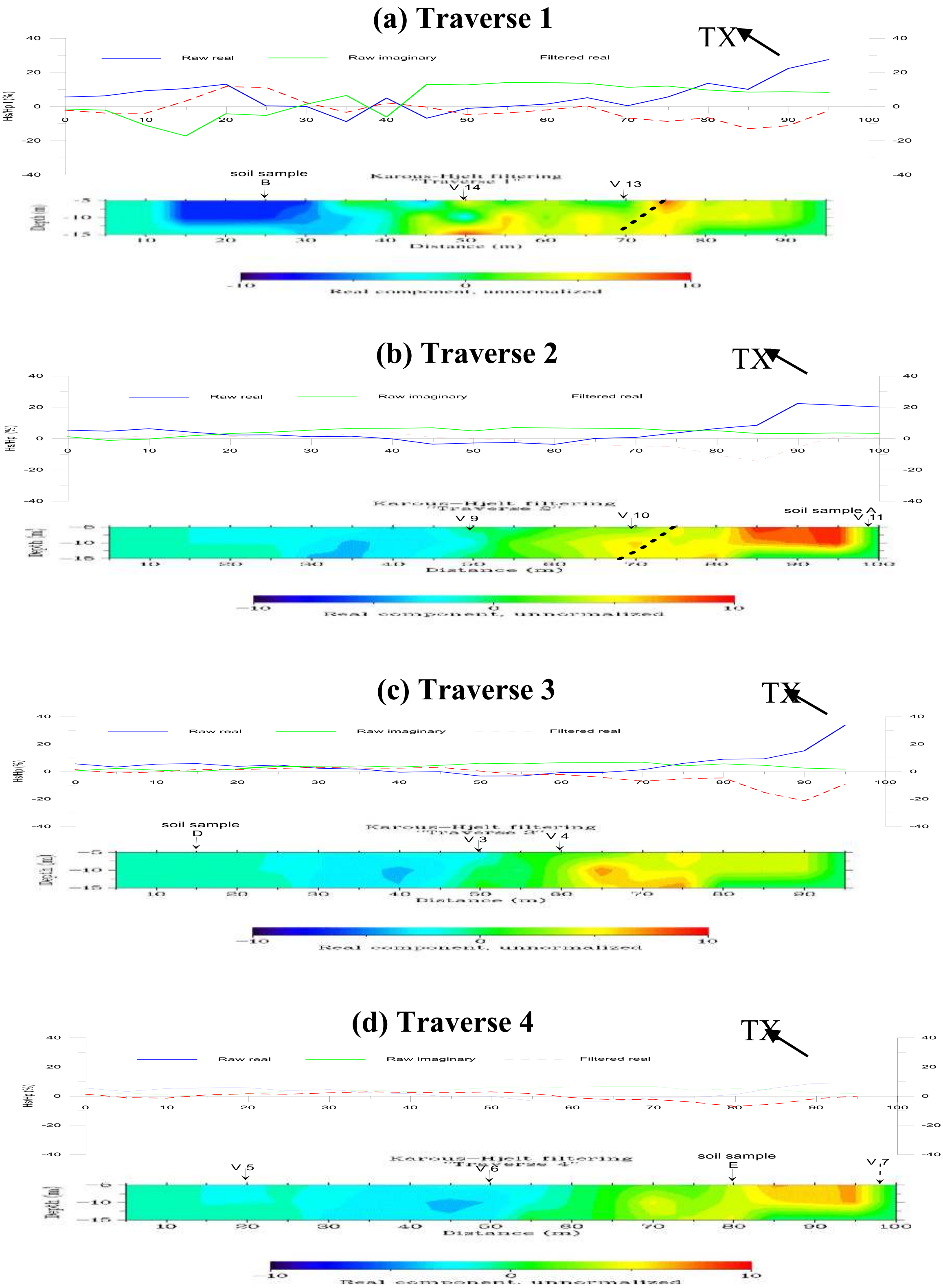

Figure 2. 2D VLF-EM current density tomographic profiles obtained from the four profiles of the SW–NE orientation.

field due to highly laterised rock in the form of a thick section of clayey topsoil in the study area that created errors in the VLF-EM data quality. These envisaging errors in the interpretation of the VLF-EM data were compensated for with the data results interpreted through the dipole–dipole electrical imaging technique.

Generally, the generated 2D electromagnetic tomographic profiles revealed similar patterns of current density

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

distribution with depth range from 5–15 m in the area. However, characteristic resistive patterns are observed, revealing two closely located boulder-like structures cutting across the profiles at the southwestern end and close to the center of the traverses. The attenuation anomaly of the EM field around the structures is observed to be occasioned by the intense weathering impact of the parent charnockitic rock, while the signature arising from the other resistive body towards the center and dipping southward is better resolved. The 2D VLF-EM profiles of Traverses 1 and 2 revealed more pronounced pockets and massive conductive patterns diagnostic of geologic structures such as massively weathered suspended bedrocks or clayey subsoil that extend through the northeastern part of the sections. In addition, linear features identified as fractures were observed at a distance of about 50 to 80 m and 85 to 90 m along these traverses, respectively. The selection of the VES locations was based on the mapped geologic structures/features from the interpreted VLF-EM data and that of the dipole–dipole electrical imaging.

4.2. Dipole–dipole array imaging technique results

As a complementary tool to the VLF geophysical prospecting technique application in the mapping and characterizing of the subsurface lithology in the study area, the dipole–dipole array imaging technique revealed characteristic patterns of variation in the resistivity within the subsurface (figures 3(a)–(f)). The obtained results enhance the delineation and mapping of the possible existing geologic structures/features in 2D form from which their geometries (lateral and vertical) were determined with good resolution (Lebourg and Frappa 2001) in comparison with the VLF-EM–based KH tomographic profile results (figures 2(a)–(d)). The mapped topsoil (generally at a depth range of 0 to 2.5 m) across the six modeled dipole–dipole resistivity tomographic 2D sections (figure 3) is highly heterogeneous and composed mostly of conductive clayey materials with resistivity values skewed generally towards less than 50 Ohm-m. Beneath the mapped topsoil are revealed pattern diagnostics of weathered parental rock with vertical resistivity structures of varying lateral extent. Figures 3(e) and (f) are typical of the 2D model resistivity structures which allow a 3D view of the bedrock geometry in the study area. In figure 3(e), the conductive structures mapped at the northwestern segment were observed to coincide with the highly conductive structures delineated at the southwestern part of figure 3(a). However, the geometry in figure 3(e) suggested an area of bedrock depression revealed from the convex shape of the high-resistivity contrast associated with the delineated conductive structure. On the other hand, the 2D model resistivity pseudo-sections of figures 3(b)–(d) delineated various resistive vertical structures as revealed by their resistivity pattern anomalies observed at the southwestern end of the profile. Qualitatively, the delineated resistive vertical structures can be linked to the extension of the massive bedrock delineated at the southeastern part of the resistivity profile in figure 3(e). Those mapped conductive structures at greater depth, having characteristics of lithological contact/fracture and bedrock depression, were found to be correlated with the identified linear features mapped at shallower depth on the VLF-EM–interpreted tomographic profiles (figures 2(a)–(d)). Positions V16 and V2 were guided by these mapped suspected geologic features. In figure 3(f), the positions labeled V9 and V3 were identified to be edge or contact between conductive or resistive bodies, while the point labeled C coincided with the highly conductive zone along the profile, where a soil sample was obtained for further geotechnical test. Within the site, intense weathering of gneissic charnockitic bedrock that possesses a planar penetrative fabric was observed, which was also highlighted in the current density distribution pattern revealed by the VLF-EM tomographic profiles obtained in the study area (figures 2(a)–(d)). Positions V9 and V3, as well as the point labeled C for the soil sample point obtained for the geotechnical test analysis in figure 3(f), were also based on the suspected geologic features identified.

4.3. Geoelectric data modeling results

On the basis of the preliminary geophysical results obtained from both VLF-EM and 2D dipole–dipole resistivity imaging approaches, 16 VES points (as shown in figures 1(b) and 3) were occupied in the area. Table 1 shows the determined geoelectrical parameters (layer resistivity and thickness values) and the curve types obtained from both qualitative and quantitative interpretation of the acquired VES data. Shown in figures 4(a)–(c) are the three typical field curve types characterizing the study area. The sounding curves obtained allow for the assessment of electrofacie changes in the subsurface geology/lithology in terms of resistivity and thickness of the geoelectric layer sequence. In figures 4(a)–(c), the characteristic sounding curves vary from three-layer (type A and K) to predominant four-layer (type KH) types. With the determined geoelectric parameter results, the geoelectric sections revealing the geoelectric layers diagnostic of lithological sequence and bedrock configuration in the area were generated (figures 5(a)–(f)). Interpreting figures 5(a)–(f), the boundary of each lithological subsurface characterization underlying the area was quite revealing. These sections identified four geoelectric sequences: silty/clayed topsoil, clayey to lateritic substratum, partially/fully saturated weathered layer, and intensely fractured/fresh bedrock that varied from place to place. The delineated topsoil layer was characterized by clayey material with resistivity and thickness values in the range of 38 to 142 Ohm-m and 0.7 to 3.1 m, respectively. The lateritic substratum layer had resistivity values in the range of 97 to 563 Ohm-m and thickness varying from 1 to 10.7 m. The estimated depth to bedrock in the area varies from 21 to 23.9 m, while the weathered layer was characterized by resistivity and thickness values ranging from 44 to 215 Ohm-m and 2.7 to 17. 5 m, respectively. These identified depression zones, as well as the partially saturated weathered layer delineated, are strongly in support of the

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

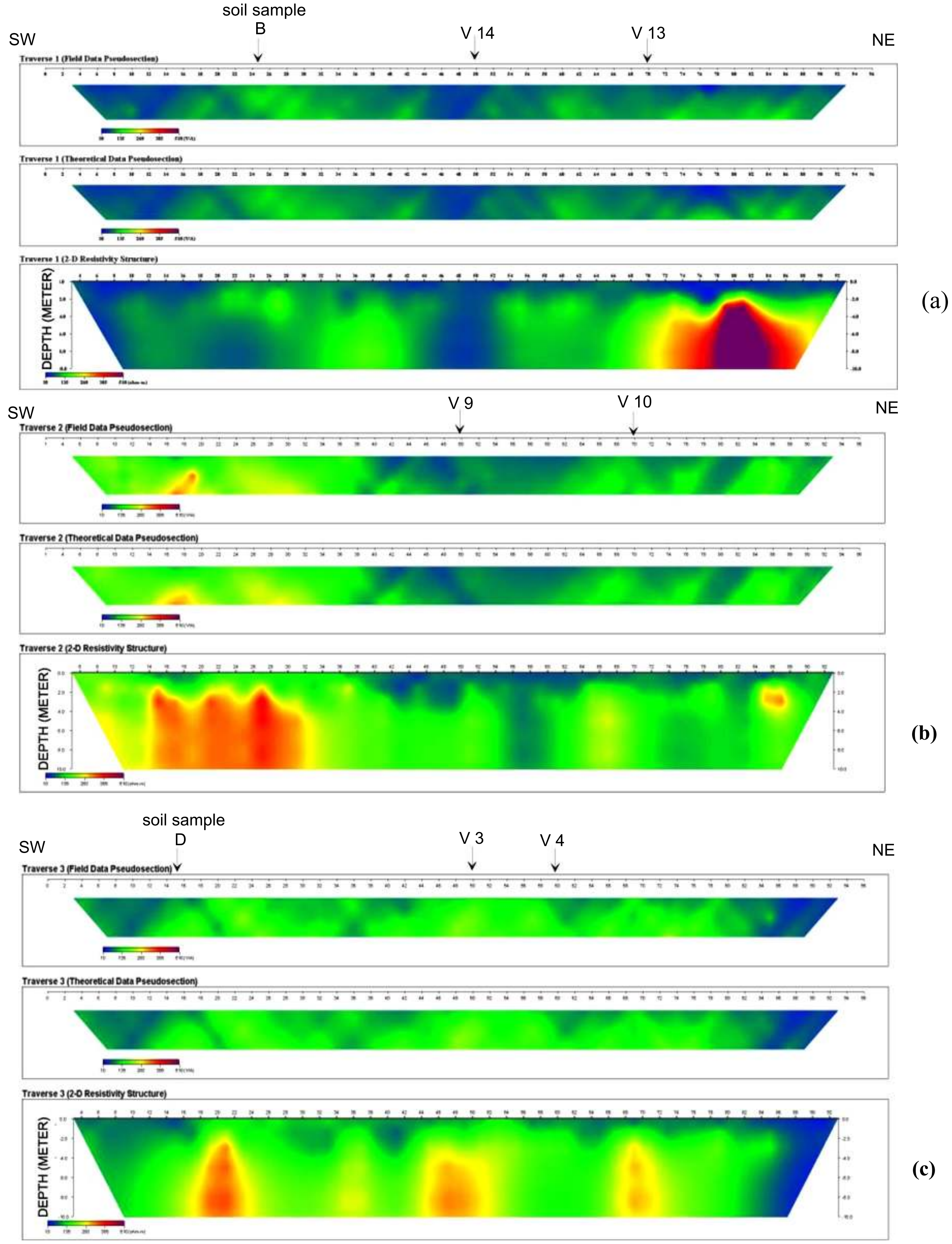

Figure 3. 2D dipole–dipole electrical resistivity tomographic profiles showing 2D high-resolution images of the subsurface geology; four 2D profiles along the SW–NE VLF-EM profiles, and other 2D dipole–dipole profiles obtained to highlight the resistivity distribution pattern along the NW–SE orientation.

occurrence of fracturing or intense weathering of the bedrock underlying the study area. It can thus be deduced from these generated geosections that information on the configuration of the subsurface layers, the nature/competence of the subsoil, the bedrock topography, and its structural disposition in the area have been provided. In

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

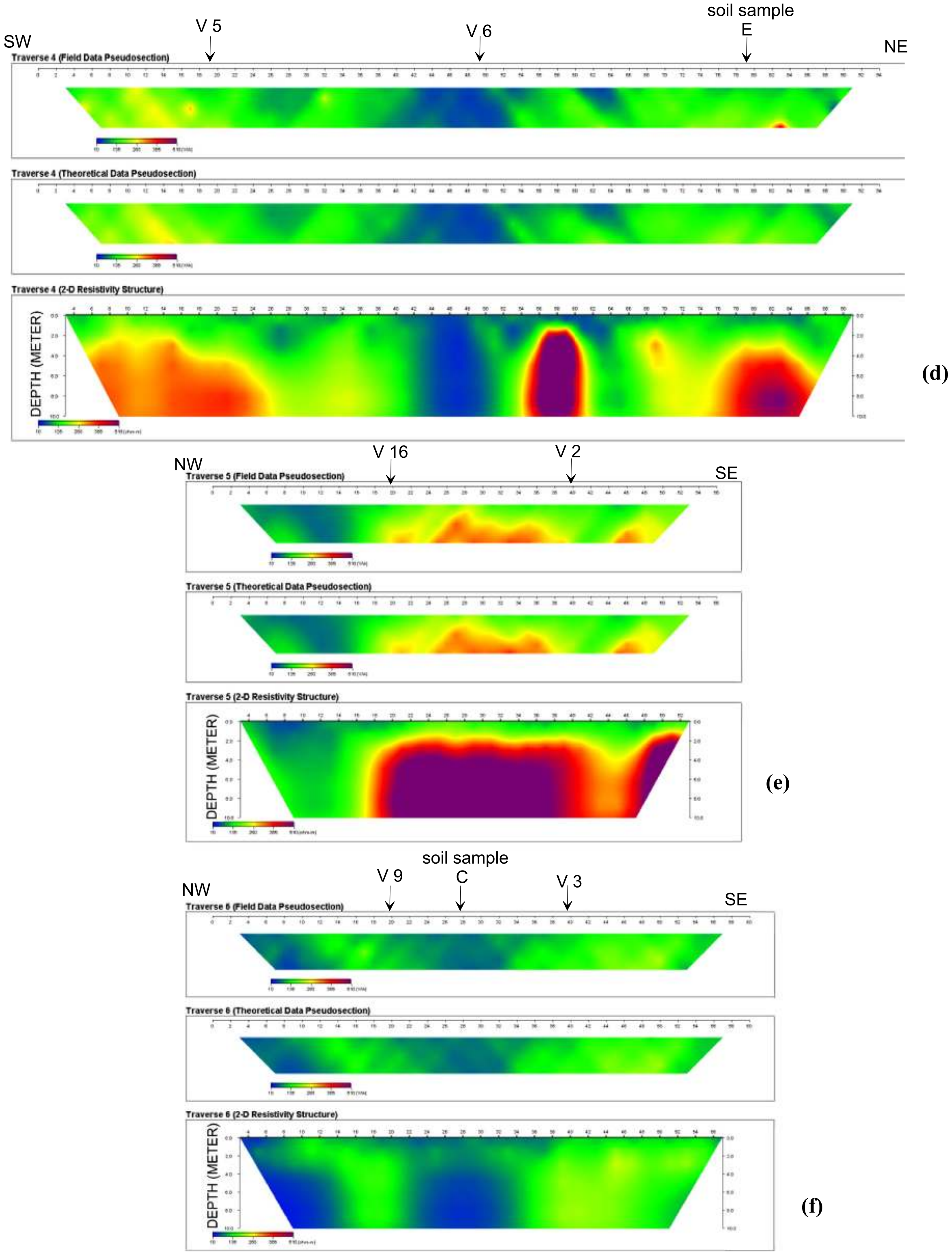

Figure 3. (Continued.)

accordance with Adewumi and Olorunfemi (2005) and Adeoti *et al* (2016), such engineering information is often needed for proper foundation decisions as to the design of civil engineering structures and their location, to suit the variable character of the bedrock.

4.4. Geotechnical investigation results

Shown in figures 1(b), 2, and 3 are the five sample collection points (A, B, C, D, and E). Some geotechnical properties determined from the laboratory test analysis on these samples

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

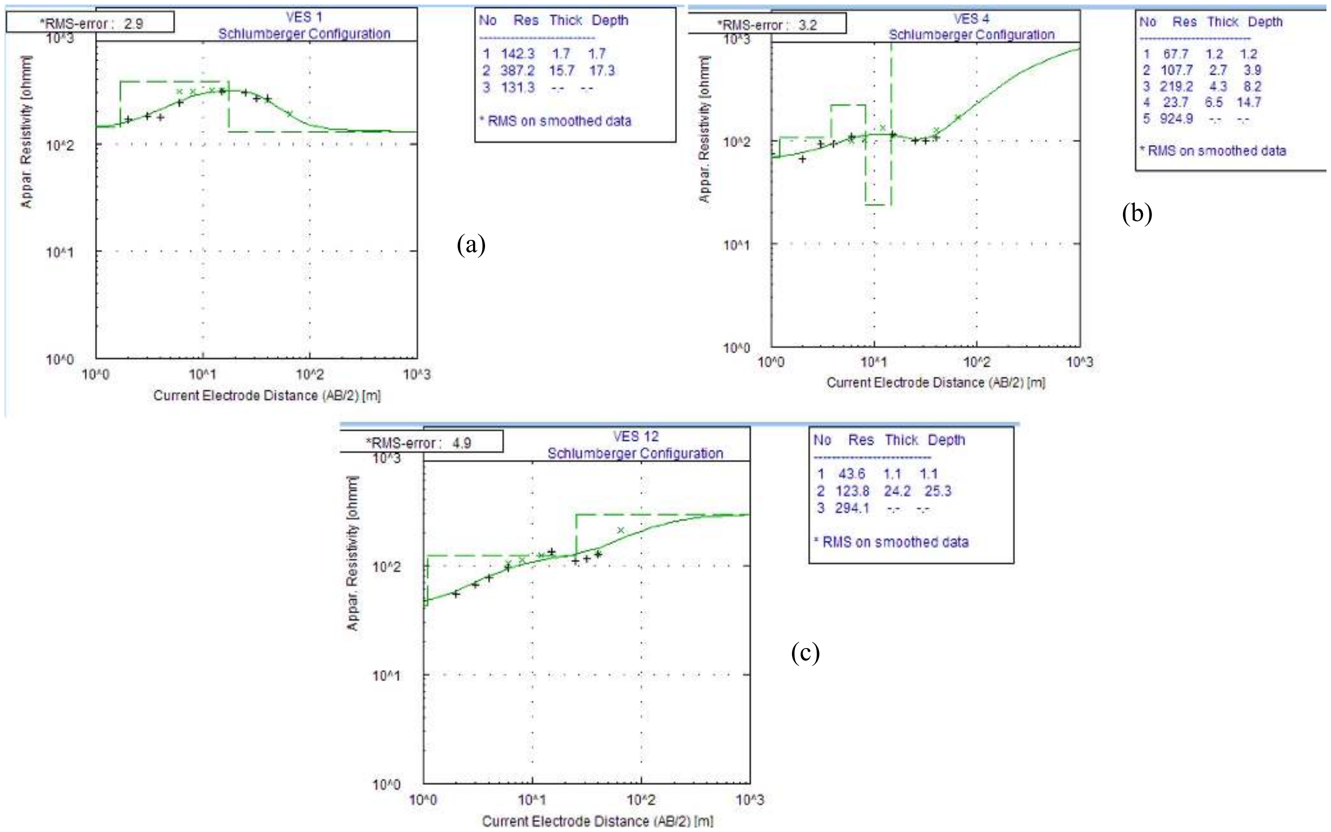

Figure 4. Three characteristic sounding curve types obtained from the inverted VES data used in evaluating electrofacie changes in the subsurface lithology from the study area.

are presented in table 2. The natural moisture content (NMC) of the tested soil samples ranges from 19.5% to 20.6% (column 2 of table 2). This range of NMC values according to Jegede (2000) implies that the soil sample at 1 m depth is of medium compaction in its natural state and may not be under serious threat when there is high rainfall. This is probably because the NMC parameter of soil is largely a function of the intensity of rain, the depth of sample collection, as well as the texture of the soil. The results of the soil grain size analysis test (percentage finer passing of 0.075 mm sieve size) show values in a range between 75 and 78 (column 3 of table 2). The computed average values for the samples' percentage passing of 0.075 mm sieve size is 75%. By the gauging standard of the Federal Ministry of Works and Housing (FMWH) (1972), 75% is at the upper limit of the 35% recommended standard. Therefore, the area soil's engineering suitability properties for foundation material is rated moderately fair. This result is in agreement with the grading curve analysis (figure 6) conducted on the area subsoils, which classified the soil samples tested to be a well-graded soil with fine particles, which is typical of low-silt and high-clay-material content.

Similarly, the liquid and plastic limit results (columns 4 and 5 of table 2) also give an indication of high clayey content in the soil samples. The determined plastic index (PI) (column 6) result for the samples has an average value of 24.2%. These PI results, according to Jegede (2000), are also at the upper limit of the 20% engineering standard for foundation materials. Thus, the soil samples can be rated as exhibiting fair to moderate engineering properties for foundation materials subgrade at shallow depth. The linear linkage shrinkage (LS) values, on the other hand, vary between 7.7% and 8.2%, with 7.9% being the average value (Column 7). With this LS value, the soil in the area is classified to be an inactive and

Table 1. Summary of geoelectric parameters.

VES No.	Resistivity (Ω-m) $\rho_1/\rho_2/\ldots/\rho_n$	Depths (m) $d_1/d_2/\ldots/d_{n\text{-}1}$	Curve type
1	142/367/131	1.7/15.7	K
2	83/563/66/1280	1.1/7.4/20.9	KH
3	74/126/57/213	1.0/2.7/13.2	K H
4	68/108/210/24/925	1.2/2.7/4.3/6.5	KH
5	115/164/58/324	1.0/8.4/9.2	KH
6	90/368/104/220	0.8/1.0/23.9	KH
7	115/502/90/167	0.7/1.4/37.4	KH
8	38/97/53/72	0.7/1.9/15.8	KH
9	64/96/225/36/455	1.0/2.7/5.5/11.8	KH
10	84/100/56/155	1.3/3.6/2.5	KH
11	112/338/156/3098	2.8/9.8	KH
12	44/124/294	1.1/24.2	A
13	75/200/66/137	3.1/4.9/9.4	KH
14	80/97/46/202	0.9/10.7/9.6	KH
15	93/215/25	2.1/19.3	H
16	75/266/140	1.0/4.4	H

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

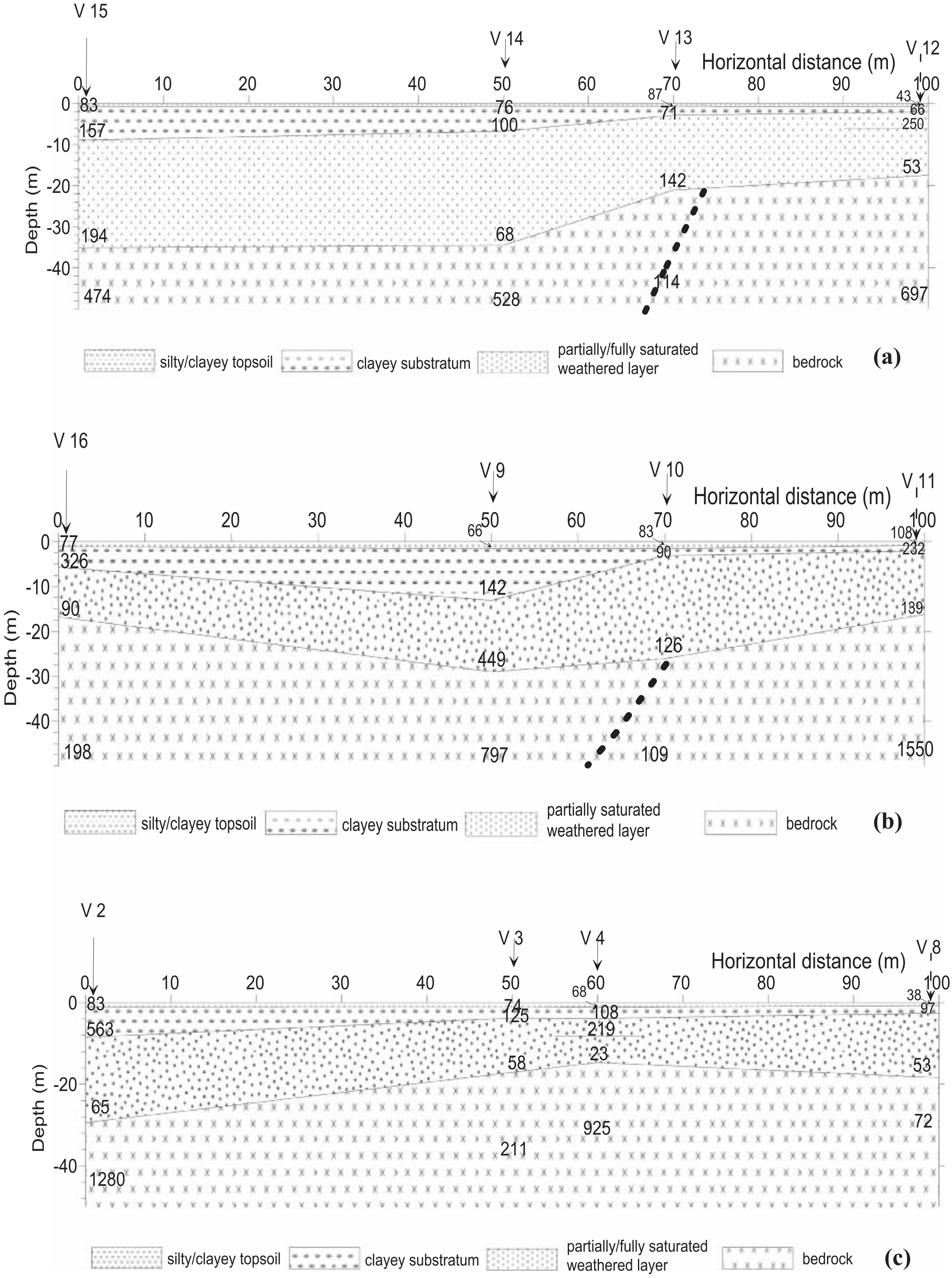

Figure 5. (a)–(f) Geoelectric sections derived from 2D correlation of the VES curves highlighting lithologic changes in the subsurface geology along Traverses T1–T6. (a) to (d) show the model geoelectric sections along Traverses T1–T4.

non-shrinking type. The determined LS parameter of $<8\%$ confirms the inactive and inexpansive characteristics of the area subsoil and classifies the area subsoil as a relatively good foundation material, which is at variance with other geotechnical tests and geophysical results.

4.5. Correlation of modeling results from the adopted methods

Figure 7 shows a summary of the results of the geophysical surveys conducted along the established traverses (T1–T4) in the investigated area. Regarding figure 7(a) (Traverse 1), the

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

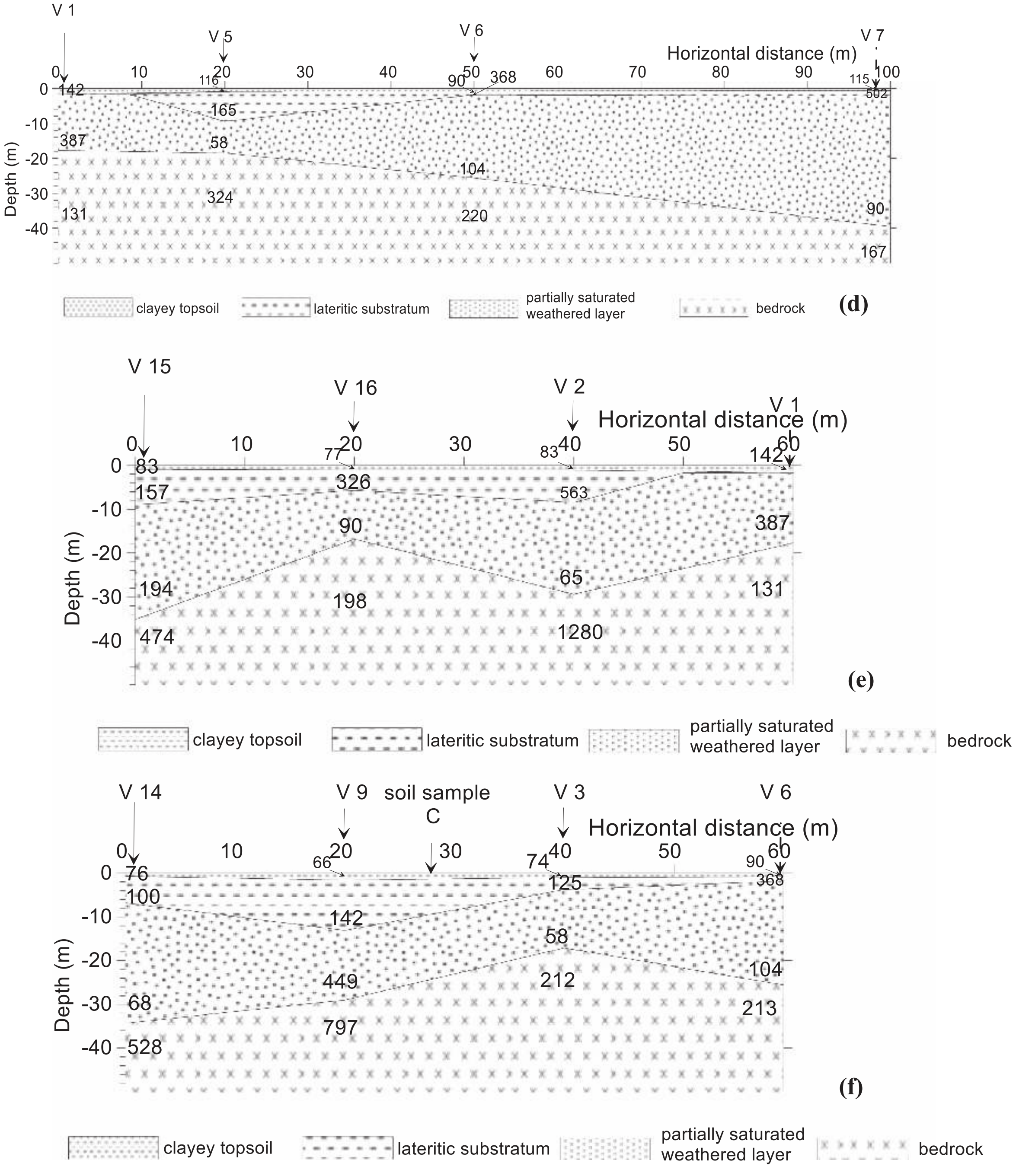

Figure 5. (Continued.)

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

Table 2. Summary of the determined geotechnical parameters.

Sample	NMC (%)	Percentage passing 0.075 mm	LL (%)	PL (%)	PI	L S (%)	S G	FI	SI	LI
A	22.4	75	60.4	36.75	24.5	7.7	2.77	6.59	0.37	−0.05
B	22.4	74.6	62.5	38.25	24.5	7.7	2.74	6.59	0.35	−0.05
C	19.5	77.8	57.3	32.90	24.4	8.2	2.78	6.59	0.34	−0.15
D	19.5	75.2	57.3	32.90	24.4	8.2	2.72	6.49	0.34	−0.15
E	20.6	74.5	55.0	31.65	23.4	7.7	2.78	6.59	0.37	−0.09

NMC: natural moisture content; LL: liquid limit; PL: plastic limit; PI: plastic index; LS: linear shrinkage, SG: special gravity; FI: flow index; SI: swell index; LI: liquid index.

GRAIN SIZE ANALYSIS

Client: Date: 7/16/2012

Project:

Location:

Borehole No. Sample No. A Depth, mt.:

Sieve Analysis

Particle Description		Particle Diameter (mm)	Mass Retained (g)	Retained (%)	Percent Passing (%)
	Cobbles	100.000			100.0
		75.000			100.0
GRAVEL	Coarse	63.000			100.0
		37.500			100.0
		19.000			100.0
		14.000			100.0
		9.500	0.00	0.00	100.0
	Fine	4.750	0.00	0.00	100.0
		2.000	9.00	1.88	98.1
SAND	Coarse	0.850	16.00	3.33	94.8
	Medium	0.425	22.50	4.69	90.1
		0.300	16.00	3.33	86.8
		0.212	21.00	4.38	82.4
	Fine	0.150	16.00	3.33	79.1
		0.106	11.00	2.29	76.8
		0.075	11.50	2.40	74.4
FINES	Clay or Silt	<0.075	356.85	74.37	
		Sum	123.00		
		Initial wgt	479.85		

Gravel =	1.9%	Gravel =	1.9%
Coarse Sand =	3.3%		
Medium Sand =	12.4%	Sand =	23.8%
Fine Sand =	8.0%		
Fines =	74.4%	Fines =	74.4%
Silt =	13.4%	Clay =	61.0%

Hydroscopic Moisture

Content % = 4.2 %

Bulk weight = 500.0 g

Dry weight = 479.8 g

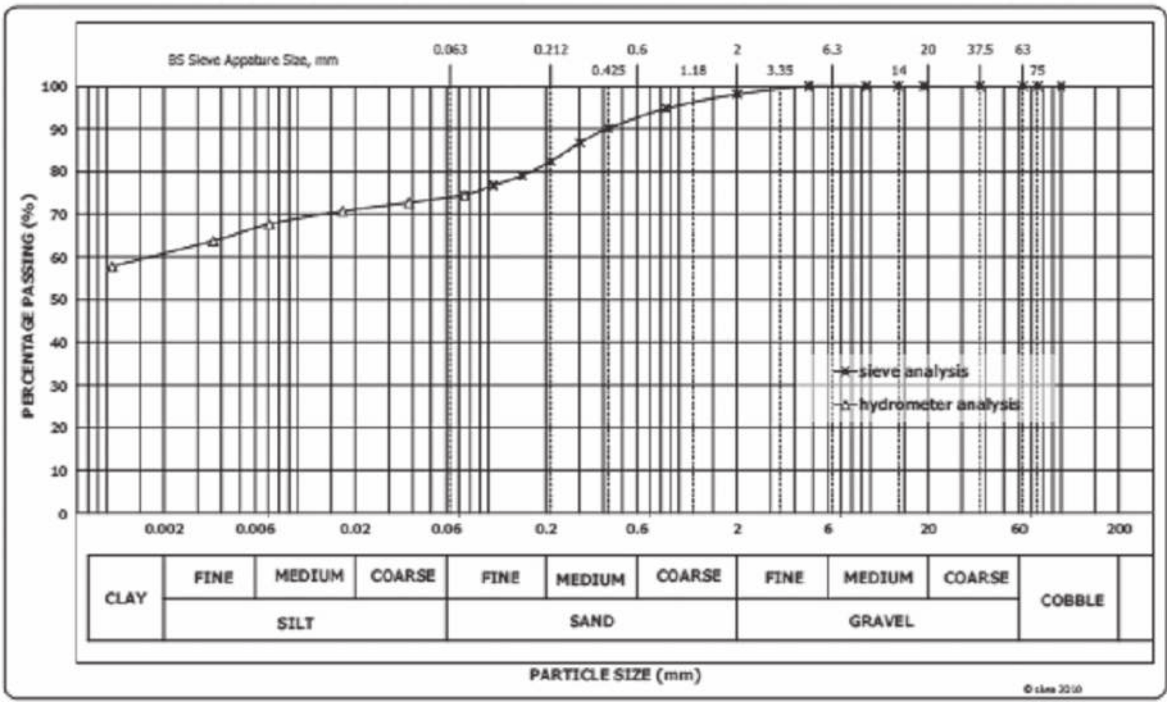

Figure 6. Typical grain size distribution curve. (Sample c.)

positive filtered real amplitude and the point of inflection of the unfiltered real of the EM signature that were identified at distances 50 and 78 m on the VLF-EM profiles coincided with the positions of the conductive zones (zones of weakness) delineated on the produced 2D VLF-EM current density section models. This also agrees with the observed low-resistivity zones (fracture/weak zones) between 40 and 50 m distance on the dipole–dipole resistivity section at depth

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

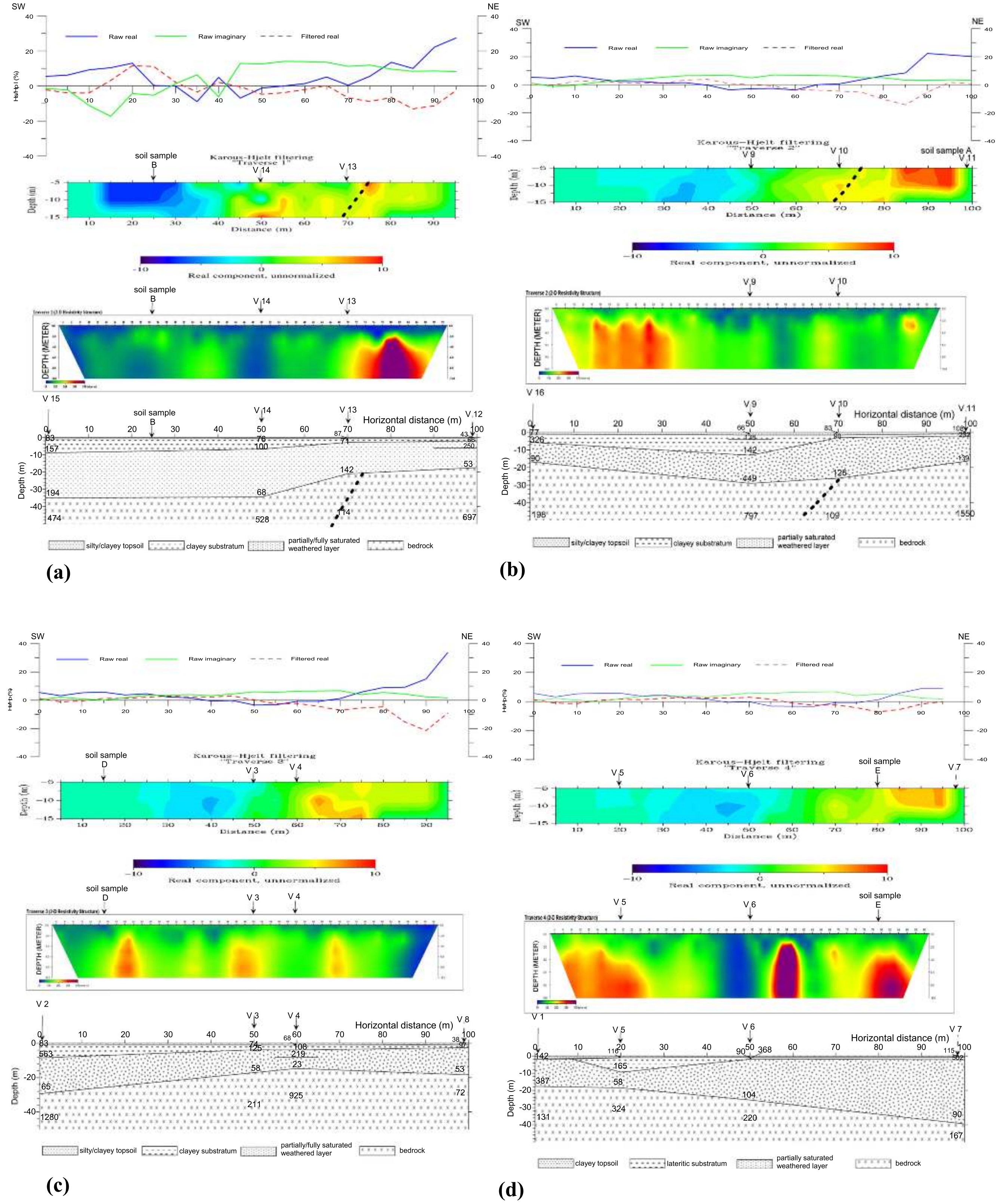

Figure 7. (a)–(d) Correlation results panel showing the VLF-EM profile, KH current density section, dipole–dipole resistivity section, and geoelectric section along traverses T1–T4, respectively.

greater than 8 m and possibly extending close to the ground level. The suspected linear feature, typical of a weak zone identified on the KH section, is found to correspond with the observed point of inflection on the VLF-EM profile and the possible lateral changes in lithology or rock boundary/contact mapped on the dipole–dipole resistivity section observed between 70 and 90 m distance. Similarly, in the 1D geoelectric section, the depression zones and partially saturated

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

weathered layer were delineated at a distance between 80 to 140 m, which was in agreement with the observed conductive zones and the linear features (rock lithological boundary/contact/probable fracture/fault) previously mapped. Complementary findings in these deployed geophysical methods are evidence of the analyzed results. Evidence of the existence of geologic features that could be inimical to good foundation development can be deduced from these results, and thus their future effects must be accommodated during the foundation design phase.

According to the VLF-EM signature manifested along the Traverse 2 profile, the peak positive of the filtered real values, which correspond to probable fracture/weak zones (weak zones), were observed at 50, 70, and 90 m distances. These zones also coincided with the conductive zones delineated on the KH section at distances between 50 and 90 m at near surface. Also, there is an occurrence of a typical dipping linear feature (probable fracture/weak zone) at the distance of 70 to 80 m from the southeastern end of the profile, which corresponds to an observed relative positive peak of the filtered real (figure 7(b)). The identified conductive zones and the linear features on both the VLF-EM profile and KH section were found to be correlated with both the low resistive shallow formation (weak zone) noticed at distances between 30 and 100 m on the dipole–dipole resistivity-section and the depression zone, as well as the partially saturated weathered layer observed in the geoelectric section (figure 7(b)). By this analysis, it has been established that the subgrade material or the subsoil in the investigated site is largely inhomogeneous. Therefore, structural engineers should consider these geophysical findings for proper foundation design in the area.

Similar geologically weak structures (conductive zones, rock contact boundary, fracture, depression zone, and weathered/saturated layer) characteristic of weak zones were also manifested based on the results from other traverses (figures 7(c) and (d)). Thus, insight into the nature of these structural dispositions and their delineation is vital to building foundation integrity assessment in the area—particularly because these weak zones largely tend to pose a threat to future civil engineering structure development in any given area.

Furthermore, from the results of geotechnical characterization, a relative agreement between the obtained geophysical results was observed in the area. From the analyzed geotechnical results, the soil plastic index (PI) values are higher on average (>20%), which typifies a medium- to high-plasticity material typical of clay formation and, according to Adeoti *et al* (2016) and Soupios *et al* (2007), is largely an incompetent material for engineering foundations. This result correlates well with the geoelectric lithological sections modeled for the area, where the delineated topsoil layer from which the collected chunk of the tested soil samples is generally made up of clayey material (figures 5(a) and (b)).

4.6. Foundational integrity assessment of the area

The assessment of the foundation competency of the area is based on the integrated results derived from both geophysical and geotechnical investigations. With the determined and interpreted geoelectric parameters of the area, the subsurface lithological characterization and the possible existence of major linear structures such as fracture/faults, representing weak zones, have been recognized to exist (figures 2 and 3). The geologic sequence beneath the study area is composed of silty/clayed topsoil, clayey substratum, partially/fully saturated weathered layer, and bedrock (figures 5(a) and (b)). Although the topsoil and near-surface expression of these weak targets/features have a strong influence on the foundational integrity of the civil engineering structures, the structures at shallow or intermediate depth might also have a serious impact.

Geoelectrically, the topsoil in the area is generally composed of clay formations. More so, from the geotechnical evaluation results of this layer (primarily the NMC, grain size, PI parameters determined, etc (table 2)), it was established that the high porosity, low permeability, and low resistivity properties of the topsoil in the area typified a clayey composition medium that is a weak foundation material. The conformity of these geotechnical parameters and the geoelectrical lower-resistivity characteristic of this layer (topsoil) confirmed the incompetency of the topsoil layer as a suitable engineering material. From the point of view of engineering and geophysics applications, this is in agreement with findings of Akintorinwa and Adeusi (2009) and Adeoti *et al* (2016) which have established that, the higher the resistivity value of a layer, the higher the competence of the layer and vice-versa. Additionally, the evaluated geotechnical parameters of the soil samples taken from the area are relatively higher than the recommended limits of 35%, 50%, 30%, and 20% maximum for the percentage finer grain size passing 0.075 mm sieve, liquid limit, plastic limit, and plastic index set by the FMWH (1972), with the exception of 8% minimum for linear shrinkage for a good foundation material (table 2). Thus, the geotechnical properties obtained from the site show that the subsoil is relatively incompetent as a foundation material.

5. Conclusions

Geophysical and geotechnical techniques have been employed to assess the foundational integrity of subsoil materials in a typical crystalline basement complex terrain, precisely for ensuring proper construction plans for civil engineering structures. Using these methods, the subsurface geology complexity, structural mapping, and relevant geotechnical parameters for foundation layer reliability have been evaluated. From the geophysical point of view, the VLF-EM and ER dipole–dipole tomographic models provide information about subsoil layers with zones of weakness/slip-surface along which movement can occur (fracture/fault). In addition, drainage channel systems and structural features that are inimical to the foundations of civil engineering structures were delineated. Complementing this is 2D vertical electrical sounding imaging that revealed the underlying geologic layer/sequence comprised of silty/clayed topsoil, clayey

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

substratum, partially/fully saturated weathered layer, and fractured bedrock. The geophysical results imply that the subsoil in the site demonstrates poor to low competence rating for foundational material, which has been attributed to the underlying porphyritic granite in the hybrid rocks and the level of weathering of the charnockitic rocks.

The evaluated geotechnical parameters of the subsoil in the area include natural moisture content, liquid limit, plastic limit, plastic index, linear shrinkage, special gravity, flow index, swell index, and liquid index. The geotechnical analysis of these parameters practically suggests the unsuitability of the subsoil in the area at that depth as a foundation material. Thus, the geophysical and geotechnical results complemented each other well.

Furthermore, this study established that geologic features that have strong impacts on the structural integrity and competency of the foundation materials are often bypassed or missed out on during conventional geotechnical evaluations due to their limited spatial dimensions (size, lateral extent, and depth) and discontinuity across the area of interest. This problem can be eliminated to a greater extent through the synergy of both geophysical and geotechnical approaches, as demonstrated in this paper. The integrated approaches presented in this paper have quantitatively established that the clayey nature of the substratum in the area of study must be considered in the design of the appropriate foundation. It is also recommended that pile foundations, which can allow structural load to be transmitted and well spread over the bedrock, be considered in proposed building and infrastructural developments.

In conclusion, this study has demonstrated the effectiveness of integrated methodologies in civil engineering work, whereby detailed geotechnical and geophysical evaluations are employed to provide cost-effective ways to evaluate the structural integrity and competency of foundation materials.

References

Adejumo S A, Oyerinde A O and Aleem M O 2015 Integrated geophysical and geotechnical subsoil evaluation for pre-foundation study of proposed site of vocational skill and entrepreneurship center at the Polytechnic, Ibadan, SW, Nigeria *Int. J. Sci. Eng. Res.* **6** 910

Adelusi A O, Akinlalu A A and Nwachukwu A I 2013 Integrated geophysical investigation for post-construction studies of buildings around School of Science area, Federal University of Technology, Akure, Southwestern, Nigeria *Int. J. Phys. Sci.* **8** 657–69

Ademeso O A 2009 Deformation traits in the charnockitic rocks of Akure area, Southwestern Nigeria *Asian J. Earth Sci.* **2** 113–20

Ademeso O A 2010 Field and petrographic relationships between the charnockitic and associated granitic rock, Akure Area, Southwestern Nigeria *Int. J. Environ. Ecol. Geol. Mining Eng.* **4** 49–53

Ademeso O A and Alabi K 2011 Geochemical characteristics of the charnockitic and associated granitic rock, Akure Area, Southwestern Nigeria *Nature and Science* **9** 194–8

Adeoti L, Ojo A O, Adegbola R B and Fasakin O O 2016 Geoelectric assessment as an aid to geotechnical investigation at a proposed residential development site in Ilubirin, Lagos, Southwestern Nigeria *Arab. J. Geosci.* **9** 338

Adewumi I and Olorunfemi M O 2005 Using geoinformatics in construction management *J. Appl. Sci.* **5** 761–7

Adeyemo I A, Omosuyi G O, Olayanju G M and Omoniyi G K 2014 Hydrogeologic and geoelectric determination of groundwater flow pattern in Alaba-Apatapiti layouts, Akure, Nigeria *Int. J. Eng. Sci.* **3** 44–52

Adeyemo I A and Omosuyi O G 2012 Hydrogeologic, electrical and electromagnetic measurements for geotechnical characterization of foundation beds at Afunbiowo, near Akure, Southwestern Nigeria *Ind. J. Sci. Technol.* **5** 2017–22

Akintorinwa O J and Adeusi F A 2009 Integration of geophysical and geotechnical investigations for a proposed lecture room complex at the Federal University of Technology, Akure, SW, Nigeria *Ozean J. Appl. Sci.* **2** 241–54

Anderson N, Croxton N, Hoover R and Sirles P 2008 *Geophysical Methods Commonly Employed for Geotechnical Site Characterization* (*Transportation Research Circular* E-C130) (Washington, DC: Transportation Research Board) (https://doi.org/10.17226/23073)

Arosio D, Brambilla D, Longoni L, Savazzi G and Zanzi L 2013 Seismic characterization of an abandoned mine site *Acta Geophysica* **61** 611–23

Ayodele E O 2009 Collapse of buildings in Nigeria—roles of reinforcement *Cont. J. Environ. Sci.* **3** 1–6

Benson K B, Payne K L and Stubben M A 1997 Mapping groundwater contamination using dc resistivity and VLF geophysical methods—a case study *Geophysics* **62** 80–6

Bowles J E 1984 *Physical and Geotechnical Properties of Soils* (*Civil Engineering Series*) Intl edn (London: McGraw-Hill)

Chung S G, Giao P H, Kim G J and Leroueil S 2002 Geotechnical characteristics of Pusan clays *Can. Geotech. J.* **39** 1050–60

Coker J O 2014 Geophysical and geotechnical assessment of foundation failure: a case study of library complex area, Lagos State Polytechnic, Ikorodu, Lagos *Nigeria Res. J. Eng. Appl. Sci.* **4** 23–8

Das B M 1998 *Principles of Geotechnical Engineering* 4th edn (Boston, MA: PWS Publishing Co.)

Delgado J, Alfaro P, Galindo-Zaldivar J, Jabaloy A, Lopez Garrido A C and Sanz De Galdeano C 2002 Structure of the Padul-Niguelas Basin (S Spain) from H/V ratios of ambient noise: application of the method to study peat and coarse sediments *Pure Appl. Geophys.* **159** 2733–49

Dipro for Windows 2001 *Dipro TM (Version 4.0.1); Processing and Interpretation Software for Electrical Resistivity Data* (Deajon: KIGAN)

Fatoba J O, Alo J O and Fakeye A A 2010 Geoelectric imaging for foundation failure investigation at Olabisi Onabanjo University minicampus, Ago-Iwoye, Southwestern Nigeria *J. Appl. Sci. Res.* **6** 2192–8

Federal Ministry of Works and Housing 1972 *Highway Manual Part 1 Road Design* (Lagos: Federal Ministry of Works and Housing)

Giao P H, Chung S G and Kwag J M 2000a An updated review of geotechnical characteristics of Pusan clay *The BK21 Invitation Lecture (Pusan, Korea, 15 May 2000)*

Giao P H, Chung S G and Yoon D D 2000b Settlement analysis of the Pusan clays with reference to reclamation projects *Proc. Intl. Symp. on Low Land Technology (Saga University, Japan, October 2000)* pp 143–52

Giao P H, Kim J H and Chung S G 2002 Application of engineering geophysics in investigation of the Pusan clays with reference to reclamation projects *Eur. J. Environ. Eng. Geophys.* **7** 201–18

Griffiths D H and Arker R D 1993 Two-dimensional resistivity imaging and modelling in areas of complex geology *J. Appl. Geophys.* **29** 211–26

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022

Holtz R D and Kovacs W D 1981 *An Introduction to Geotechnical Engineering* (Englewood Cliffs, NJ: Prentice Hall)
Jegede G 2000 Effect of soil properties on pavement failure along F209 highway at Ado-Ekiti, south-western part of Nigeria *J. Constr. Building Mater.* **14** 311–5
Jongmans D, Hemroulle P, Demanet D, Renardy F and Vanbrabant Y 2000 Application of 2D electrical and seismic tomography techniques for investigating landslides *Eur. J. Environ. Eng. Geophys.* **5** 75–89
Karous M and Hjelt S E 1983 Linear filtering of VLF dip-angle measurements *Geophys. Prospect.* **31** 782–894
Kayode J S, Adelusi A O, Nawawi M N M, Bawallah M and Olowolafe T S 2016 Geo-electrical investigation of near surface conductive structures suitable for groundwater accumulation in a resistive crystalline basement environment: a case study of Isuada, southwestern Nigeria *J. Afr. Earth Sci.* **119** 289–302
Lebourg T, Binet S, Tric E, Jomard H and El Bedoui S 2005 Geophysical survey to estimate the 3D sliding surface and the 4D evolution of the water pressure on part of a deep seated landslide *Terra Nova* **17** 399–406
Lebourg T and Frappa M 2001 Mesures géophysiques pour l'analyse des glissements de terrain *Revue Francaise de Géotechnique* **96** 33–40
Lebourg T, Tric E, Guglielmi Y, Cappa F, Charmoille A and Bouissou S 2003 *Geophysical Survey to Understand Failure Mechanisms Involved on Deep Seated Landslides* (Nice: EGS)
Longoni L, Papini M, Arosio D, Zanzi L and Brambilla D 2014 A new geological model for Spriana landslide *Bull. Eng. Geol. Environ.* **73** 959–70
Longoni L, Papini M, Brambilla D, Arosio D and Zanzi L 2016 The role of the spatial scale and data accuracy on deep-seated gravitational slope deformation modeling: the Ronco landslide, Italy *Geomorphology* **253** 74–82
Luna R and Jadi H 2000 Determination of dynamic soil properties using geophysical methods *Proc. 1st Int. Conf. on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure Geophysics* vol 3 (Saint Louis, MO: Federal Highway Administration) pp 1–15
Mogaji K A 2016 Combining geophysical techniques and multi-criteria GIS-based application modeling approach for groundwater potential assessment in southwestern Nigeria *Environ. Earth Sci.* **75** 1181
Ofomola M O, Adiat K A N, Olayanju G M and Ako B D 2009 Integrated geophysical methods for post foundation studies, Obanla staff quarters of the Federal University of Technology, Akure, Nigeria *Pac. J. Sci. Technol.* **10** 93–111
Olayanju G M 2011a Engineering geophysical investigation of a flood zone: a case study of Alaba Layout, Akure, Southwestern Nigeria *J. Geol. Mining Res.* **3** 193–200 (http://academicjournals.org/ijwree)
Olayanju G M 2011b Very low frequency—electromagnetic (VLF-EM) and Offset Wenner resistivity survey of spring sources for groundwater development *Int. J. Water Resour. Environ. Eng.* **3** 324–40
Othman A A A 2005 Construed geotechnical characteristics of foundation beds by seismic measurements *J. Geophys. Eng.* **2** 126–38
Oyedele K F, Oladele S and Adedoyin O 2011 Application of geophysical and geotechnical methods to site characterization for construction purposes at Ikoyi, Lagos, Nigeria *J. Earth Sci. Geotech. Eng.* **1** 87–100
Parolai S, Borman P and Milkreit C 2001 Assessment of the natural frequency of the sedimentary cover in the Cologne area (Germany) using noise measurements *J. Earthq. Eng.* **5** 541–64
Parolai S, Borman P and Milkreit C 2002 New relationships between *Vs*, thickness of sediments and resonance frequency calculated by H/V ratio of seismic noise for the Cologne area (Germany) *Bull. Seismol. Soc. Am.* **92** 2521–7
Rahaman M A 1988 Review of the basement geology of south-western part of Nigeria ed C A Kogbe *Geology of Nigeria* (Nigeria: Rock View (Nig) Limited) pp 39–59
Ritz J C, Parisot S, Diouf A, Beauvais F, Dione F and Niang M 1999 Electrical imaging of lateritic weathering mantles over granitic and metamorphic basement of eastern Senegal, West Africa *J. Appl. Geophys.* **41** 335–44
Robain H, Descloitres M, Ritz M and Yene Atangana Q 1996 A multiscale electrical survey of a lateritic soil system in the rain forest of Cameroon *J. Appl. Geophys.* **34** 237–53
Rubin Y and Hubbard S 2005 *Hydrogeophysics* (Dordrecht: Springer) p 523
Santamarina J C, Klein K A and Fam M A 2001 *Soils and Waves* (New York: Wiley)
Seaton W J and Dean T 2004 Engineering site characterization with electrical resistivity surveys *North American Society for Trenchless Technology (NASTT), NO-DIG 2004 (New Orleans, LA, 22–24 March 2004)* paper C-4-03-1
Sharma S P and Barawal V C 2005 Delineation of groundwater-bearing fractures zone in hardrock area integrating very low frequency electromagnetic and resistivity data *J. Appl. Geophys.* **57** 155–66
Sharma V P 1997 *Environmental and Enginering Geophysics* (Cambridge: Cambridge University Press) pp 40–5
Socco L V, Foti S and Boiero D 2010 Surface-wave analysis for building near-surface velocity models—established approaches and new perspectives *Geophysics* **75** A83–102
Socco L V and Strobbia C 2004 Surface-wave method for near-surface characterization: a tutorial *Near Surf. Geophys.* **2** 165–85
Soupios P, Papazachos C B, Vargemezis G and Savvaidis A 2006 *In situ* geophysical investigation to evaluate dynamic soil properties at the Ilarionas Dam, Northern Greece *Proc. 2nd Int. Conf. Advances in Mineral Resources Management and Environmental Geotechnology (Hania, Crete, 25–27 September 2006)* pp 49–56
Soupios P M, Georgakopoulos P, Papadopoulos N, Saltas V, Andreadakis A, Vallianatos F, Sarris A and Makris J P 2007 Use of engineering geophysics to investigate a site for a building foundation *J. Geophys. Eng.* **4** 94–103
Sultan S A and Santos F M 2009 Combining TEM/resistivity joint inversion and magnetic data for groundwater exploration: application to the northern part of Greater Cairo, Egypt *Environ. Geol.* **58** 521–9
Sumanovac F and Weisser M 2001 Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains *J. Appl. Geophys.* **47** 13–28
Sundarajian N, Srinivas Y, Chary M N, Nandakunmar G and Chary A H 2004 Delineation of structures favourable to groundwater occurrence employing seismic refraction method—a case study from Tiruvuru, Krishna District, Andhra Pradesh *J. Earth Syst. Sci.* **113** 259–67
Tanaka H, Mishima O, Tanaka M, Park S Z, Jeoung G H and Locat J 2001 Characterization of Yangsan clay, Pusan, Korea *Soils and Foundations* **49** 651–60
Vander Velper B P A 2004 RESIST Version 1.0 resistivity depth sounding interpretation software *MSc Research Project* ITC, Delft, The Netherlands
Venkateswara V R, Srinivasa R, Prakasa R B S and Koteswara R P 2004 Bedrock investigation by seismic refraction method—a case study *J. Ind. Geophys. Union* **8** 223–8
Woodward J 2005 *An Introduction to Geotechnical Processes* (New York: Spon) p 328

Downloaded from https://academic.oup.com/jge/article/14/3/675/5112918 by guest on 21 August 2022