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Assessment of subsoil characteristics by electrical resistivity method for engineering, groundwater and environmental impact at a proposed estate in a basement complex terrain—a case study from Southwestern Nigeria

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Abstract

We present an integrated site investigation of a proposed estate with a view to generating baseline data required for safe design and construction of structures and groundwater schemes, installation and protection of utilities, and post-construction environmental issues. An electrical resistivity survey involving 1D and 2D imaging techniques was involved. The 1D resistivity imaging involved the Schlumberger Vertical Electrical Sounding (VES) with half current electrode spacing of 1–125 m, whose data were interpreted for layer resistivities and thicknesses using segment-by-segment curve matching and 1D forward modeling with W-Geosoft/WinSev 5.1 code. The 2D dipole-dipole resistivity imaging utilized 20 m dipole length and an expansion factor (n) ranging from 1 to 5. The 2D data were inverted to 2D resistivity images with DIPRO software. The 1D and 2D interpretation models delineated five subsurface layers comprising topsoil, fill, laterite, weathered basement, and fresh basement. The weathered basement is the main aquifer with thicknesses ranging from 11.9 to 64.4 m with prospect for groundwater development. The essentially lateritic subsoils in the upper 10 m with resistivity values generally > 450 Ωm are adjudged moderately to highly competent. The low-porosity/permeability lateritic layer overlying the weathered layer aquifer constitutes a sealant against infiltrating pollutant with the groundwater significantly protected. Except within the stream channel, the soils/subsoils are practically non-corrosive.

Keywords Subsoil characterization · Engineering/groundwater development · Environmental impact · Estate development · Basement terrain

Introduction

Estate development (building construction) is on the list of major infrastructural projects including road and dam construction and large-scale groundwater development that require environmental impact assessments (EIA) prior to the commencement of construction work as enabled by the Nigerian Federal Ministry of Environment and State Environments Agencies (EIA 1992). One of the major

components of the EIA is the baseline description of the environment (FMENV 1995). This includes the nature of the soil/subsoil as a means of assessing the engineering competence, suitability as a medium for electrical system earthing, the degree of corrosiveness, and the protective capacity, delineation, and estimation of the overburden thicknesses, subsurface sequence, and the geologic structures or stability (seismicity) assessment, waste dump site selection, and groundwater development.

When these details are available to an architect, a structural, an environmental, or water engineer, building foundations, road pavements, and dam axes are designed to suit the characteristics of the subsurface sequence. This way, structure failure (including buried metallic pipes and storage tanks) arising from geological factors and the attendant environmental impacts are prevented. High-voltage

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electrical appliances such as transformers, television and radio transmitters, and mobile telecommunication transmitters are properly earthed for the safety of connected facilities and personnel (Adegoyega and Odeyemi 2011).

The fact that the enabling acts of the Federal Ministry of Environment and the State Environmental Agencies are not effectively implemented (Keftin et al. 2009) partly accounts for the failure of civil engineering structures in the country. Most times, such structures fail because of the nature and configuration of the soil/subsoil, existing but concealed geologic structures and groundwater condition (Adenika et al. 2018; Ajayi 1987; Akintorinwa et al. 2011; Bayowa et al. 2019; Eluwole and Olorunfemi 2012; Fatoba et al. 2015; Giza and Igwe 2018; Gopal 2010; Momoh et al. 2008; Oladapo et al. 2008; Olorunfemi et al. 2000, 2004, 2005; Oni and Olorunfemi 2016; Sangodiji and Olorunfemi 2013).

This work aims to justify the inclusion of estate development in the EIA Cap 86 (EIA 1992) and establish information derivable from pre-construction feasibility studies at a proposed estate in a typical basement complex environment. Basement terrains are known to be characterized by spatial variability (laterally and in depth) in soil and subsoil properties such as lithology, mineralogy, degree of fluid saturation and chemistry, layer thickness, porosity, and permeability (Oni et al. 2020a, b). These properties significantly determine the bulk resistivity/conductivity and dielectric constant, the spontaneous potential of the soil/subsoil, the magnetic susceptibility, and velocity. Contrasts in the above properties enable the application of the electrical resistivity, electromagnetic, ground penetrating radar, magnetic, and seismic geophysical methods in site investigations.

However, in the present study, the electrical resistivity method will be engaged at a proposed estate in Ile-Ife, Osun State, Southwestern Nigeria. The method was adopted for subsurface sequence delineation, geological structure identification, and nature of soil/subsoil determination.

Geology and location of site

The proposed estate is situated at Fasina area of Ile-Ife, Ife Central Local Government Area of Osun State, Southwestern Nigeria (Fig. 1). It is confined within geographic coordinates of latitudes 7° 30′ 24.3″– 7° 30′ 37.7″ and longitudes 4° 27′ 59.4″– 4° 28′ 24.7″ of the 1984 World
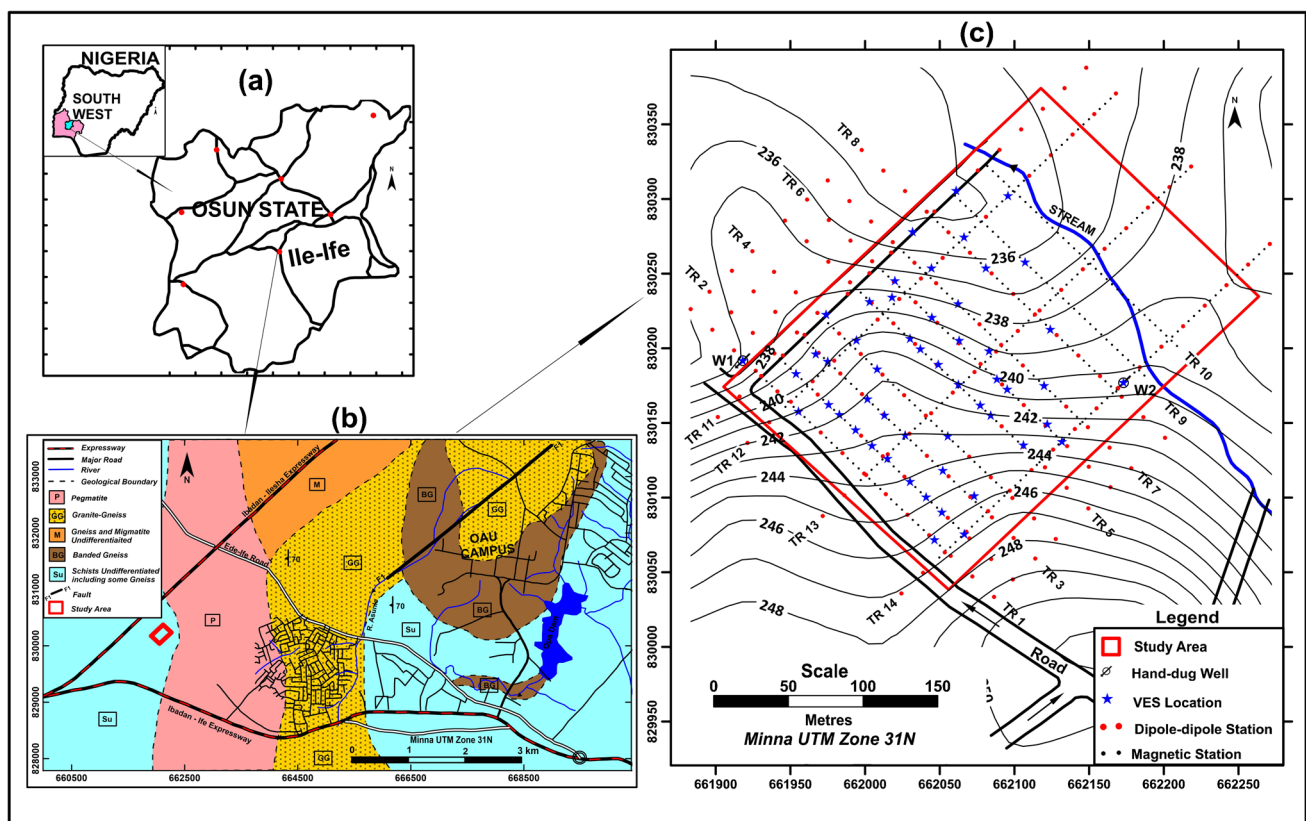

Fig. 1 Location map of **a** Osun State (insert map of Nigeria showing southwestern region) showing Ile-Ife, **b** part of Ile-Ife showing the study area with superimposed geology (extracted from Geological Survey of Nigeria, 1974), and **c** data acquisition map of the study area with superimposed topographical contour lines (modified from Olorunfemi et al., 2021)

Geodetic Coordinate System. The topography is gently undulating with elevations ranging from 235 to 247 m asl (Fig. 1c).

The site falls within the Precambrian Basement Complex rocks of Southwestern Nigeria and the Ilesa Schist Belt which is made up of mica schist, gneisses, migmatite, and pegmatite (Turner 1983). Figure 1b shows that the site is underlain by mica schist. Although the basement rock is masked by a weathered layer, dug-out chips of clayey decomposed rock from a water well (W1) at the northwestern edge of the property (Fig. 1c) contain relics of schistose structure which corroborate the mica schist basement. Weathered veins of pegmatite are exposed within some of the erosion channels.

Methodology

Ten (10) in-line N44°E trending traverses TR1–10 each 175 m long and four (4) cross-line N134°E striking traverses TR 11–14 each 300 m long were established for the survey (Fig. 1c). 2D electrical resistivity profiling with the dipole-dipole electrode array was carried out along all the traverses excluding traverses TR9 and 10 (Fig. 1c). However, the length extents of traverses TR1-10 were increased at both ends of the traverses by the equivalent of three times the dipole length (of 20 m) to give traverse lengths of 280–300 m. This was done to compensate for modeling cutoffs at both ends of the traverses. The expansion factor (n) was varied from 1 to 5. The 2D resistivity data were presented as pseudosections which were subsequently inverted into 2D resistivity images using DIPRO for Windows Software.

The resistivity images were engaged to guide the locations of a significant number of the 1D Vertical Electrical Sounding (VES). The VES adopted the Schlumberger array with half current electrode spacing (AB/2) varying from 1 to 125 m. The other VES locations were selected to ensure data representativeness. The VES curves were quantitatively interpreted using segment by segment curve marching and computer-aided 1D forward modeling (with W-Geosoft/WinSev 5.1 code) techniques. Geoelectric vertical sections and maps were produced from the results (layer resistivities and thicknesses) from which the subsurface sequence was delineated and the near-surface soils/subsoils were characterized. ABEM-made Resistivity Meter (SAS 300C Terrameter) was employed for the resistivity measurements. All measurement stations were georeferenced. Details of the principles and procedures of the electrical resistivity survey are contained in standard geophysical textbooks such as Kearey et al. (2002) and Telford et al. (1991).

Results and discussion

The VES curves range from four-layer (HA, KH, and QH) to five-layer (HKH and KHA) and six-layer (HKHA and KHKH) types. The HKH and KH curves predominate with frequencies of occurrence of 50% and 37% respectively with both constituting 87% of the total. The KH and HKH curves are characteristic of an area underlain by mica schist (Olorunfemi and Fasuyi 1993). The HKH type identifies a river fill between the topsoil and the laterite. The typical geologic sections generated along in-line and cross-line traverses (Fig. 2a–d) delineate maximum of five geologic layers with the geoelectric characteristics contained in Table 1.

The 2D resistivity structures (Fig. 3a–d) show a vertical profile that is generally composed of three geoelectric layers. The upper layer is up to 10–15 m thick (in green/yellow/brownish red color) with resistivity values varying from < 100 to 3000 Ωm but generally > 400 Ωm. The < 100 Ωm layer resistivity values were encountered along the stream channel at the northeastern edge and must be due to high level of water saturation arising from base flow from the stream. The large variations in the upper layer resistivity are due to the inhomogeneous nature of the soil/subsoil (Oladunjoye et al. 2021; Oni et al. 2020b). This layer is electrically equivalent to the upper three geoelectric/geologic layers (topsoil, fill, and laterite). The second layer is characterized by comparatively low-resistivity (< 200 to 500 Ωm) values and corresponds to the weathered layer (fourth layer of the geoelectric section). It is greenish to blue in color and yellowish in the transition (partly weathered) zone to the fresh basement. This horizon displays variable thicknesses of < 20 to > 80 m but is generally between 20 and 40 m thick. The third and bottom layer is the fresh basement with brownish red/purple color band with the gradation zone (partly weathered basement) between the weathered basement and the fresh basement in yellow color band. The layer resistivity values vary from 520 to 3000 Ωm while depths to the basal fresh basement range from < 30 to up to > 80 m but are averagely about 40 m and rarely greater than 60 m. The bedrock relief is gently undulating.

The resistivity depth slice maps (Fig. 4a–e) are at depth levels of 0–10 m, 10–20 m, 20–40 m, 40–70 m, and 70–100 m (∼ 85 m) respectively. In the upper 0–10 m (Fig. 4a), the subsoil resistivity varies from 42 to 4500 Ωm. Except for the stream channel with resistivity values < 250 Ωm, the resistivity values are generally higher than 450 Ωm and typical of lateritic soils, most especially at the western, northwestern, and southern flanks. The layer resistivity values decreased at depth range of 10–20 m to < 850 Ωm with patches of high-resistivity

Fig. 2 Geoelectric sections along in-line traverses: **a** TR8; **b** TR2 and cross-line traverses; **c** TR12; **d** TR14
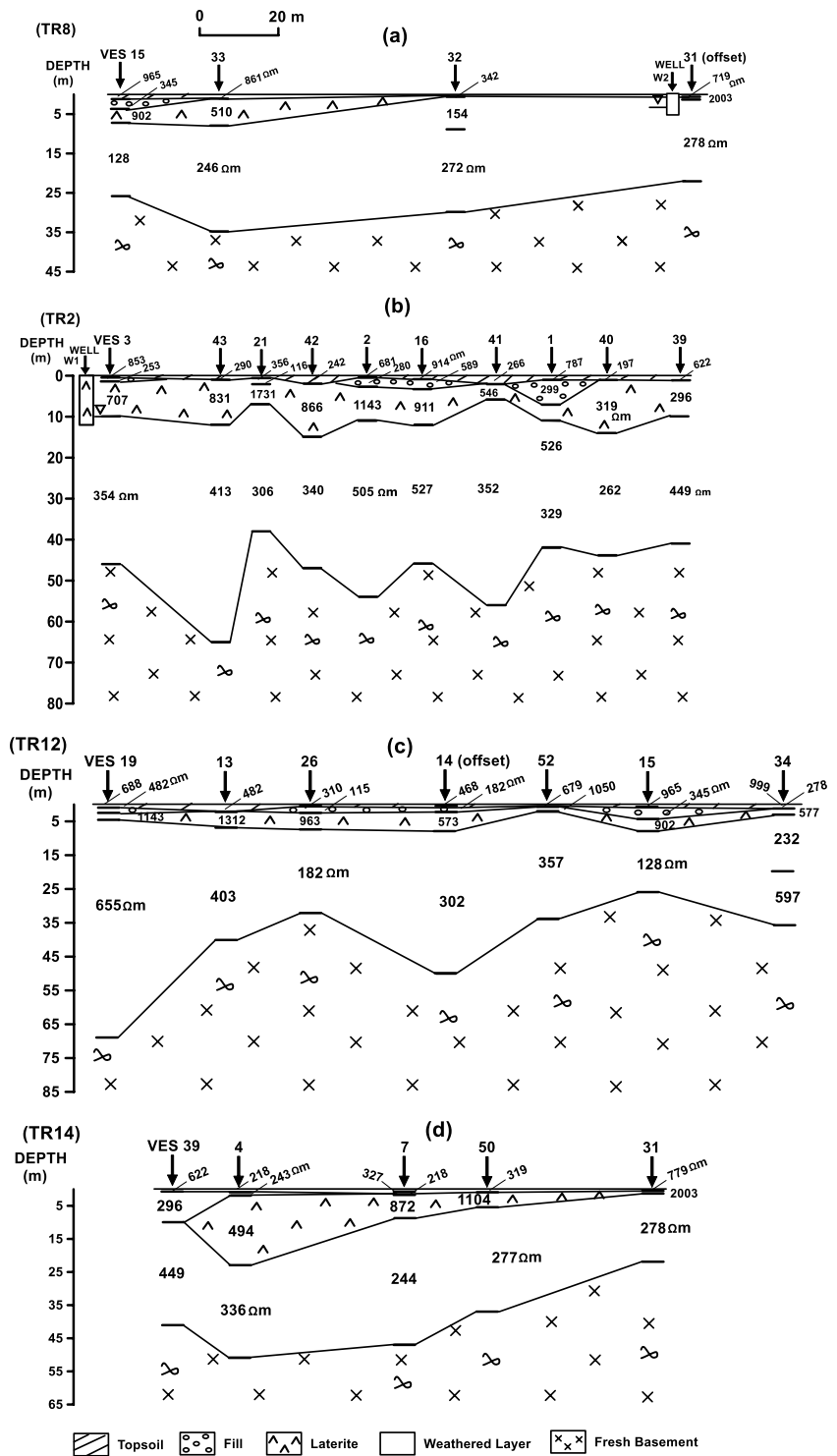
lateritic soil on western flank (Fig. 4b). The resistivity within the river channel increased from < 250 to up to 320 Ωm indicating the nearness of the resistive basement. At 20–40-m depth level (Fig. 4c), patches of very high-resistivity zone appeared in the northern, eastern, and western segments suspected to be evidences of fresh basement. The relatively low-resistivity zone (< 450 Ωm) is reflective of

the extension of the weathered layer from the 10–m depth level. At 40–70 m, the resistivity depth slice map (Fig. 4d) manifests the resistive fresh basement over a large area covering the northern, northwestern, western, southern, and eastern flanks. In these areas, depths to the basement are within the range of 40–70 m. Figure 4e shows that except at isolated locations with low-resistivity closures,

Fig. 3 2D resistivity structures along traverses: **a** TR2, **b** TR7, **c** TR11, and **d** TR14
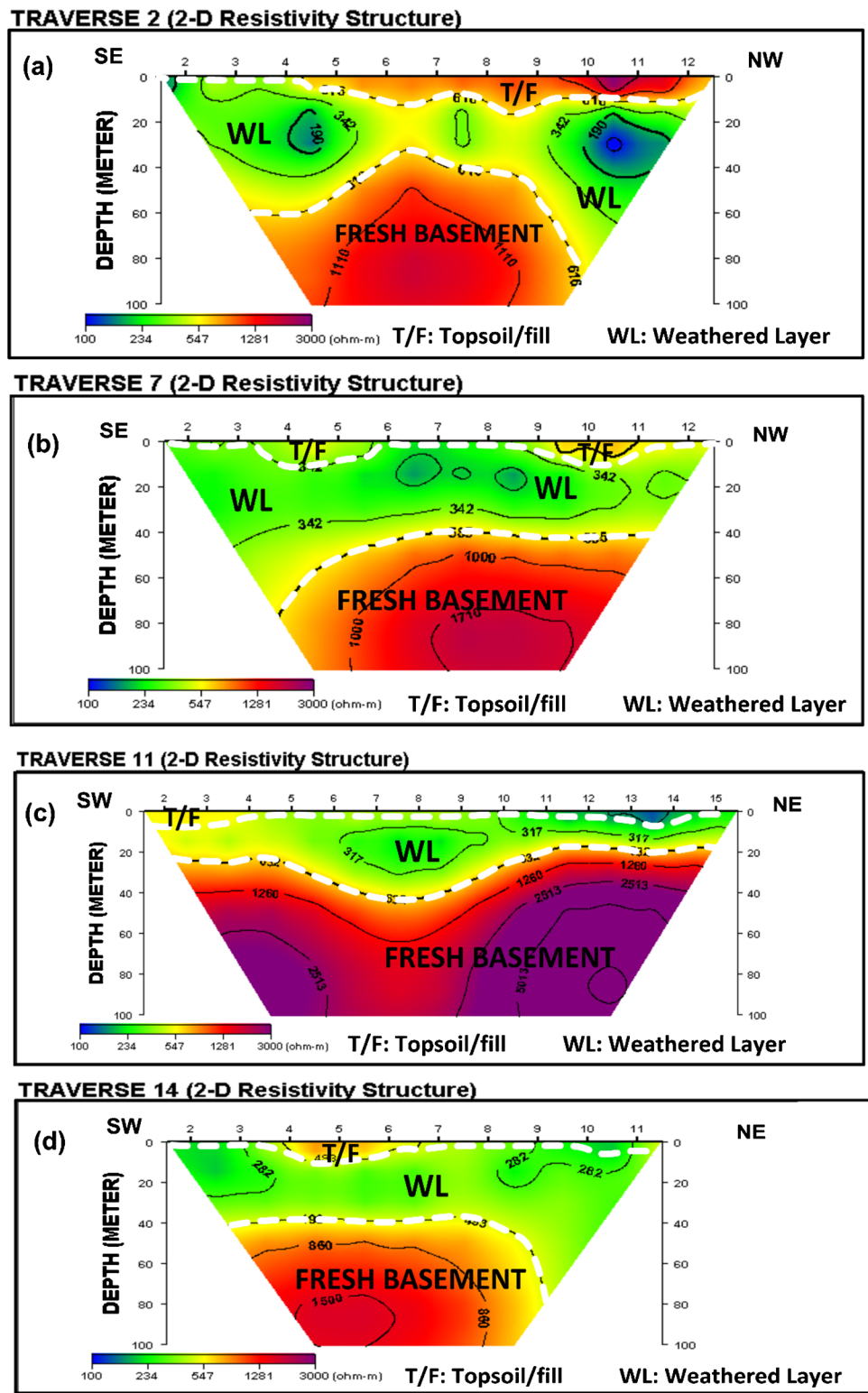
the fresh basement with resistivity values > 650 Ωm is reached at depth level that would rarely exceed 70 m. The geoelectric sections show maximum depth to fresh basement bedrock of 65 m and 69 m respectively beneath sounding points 19 and 43 (Fig. 2b, c).

The essence of a pre-construction site investigation is to enable the assessment of the nature of the soil/sub-soil and the engineering and hydro-geological character-istics required for civil engineering foundation design,
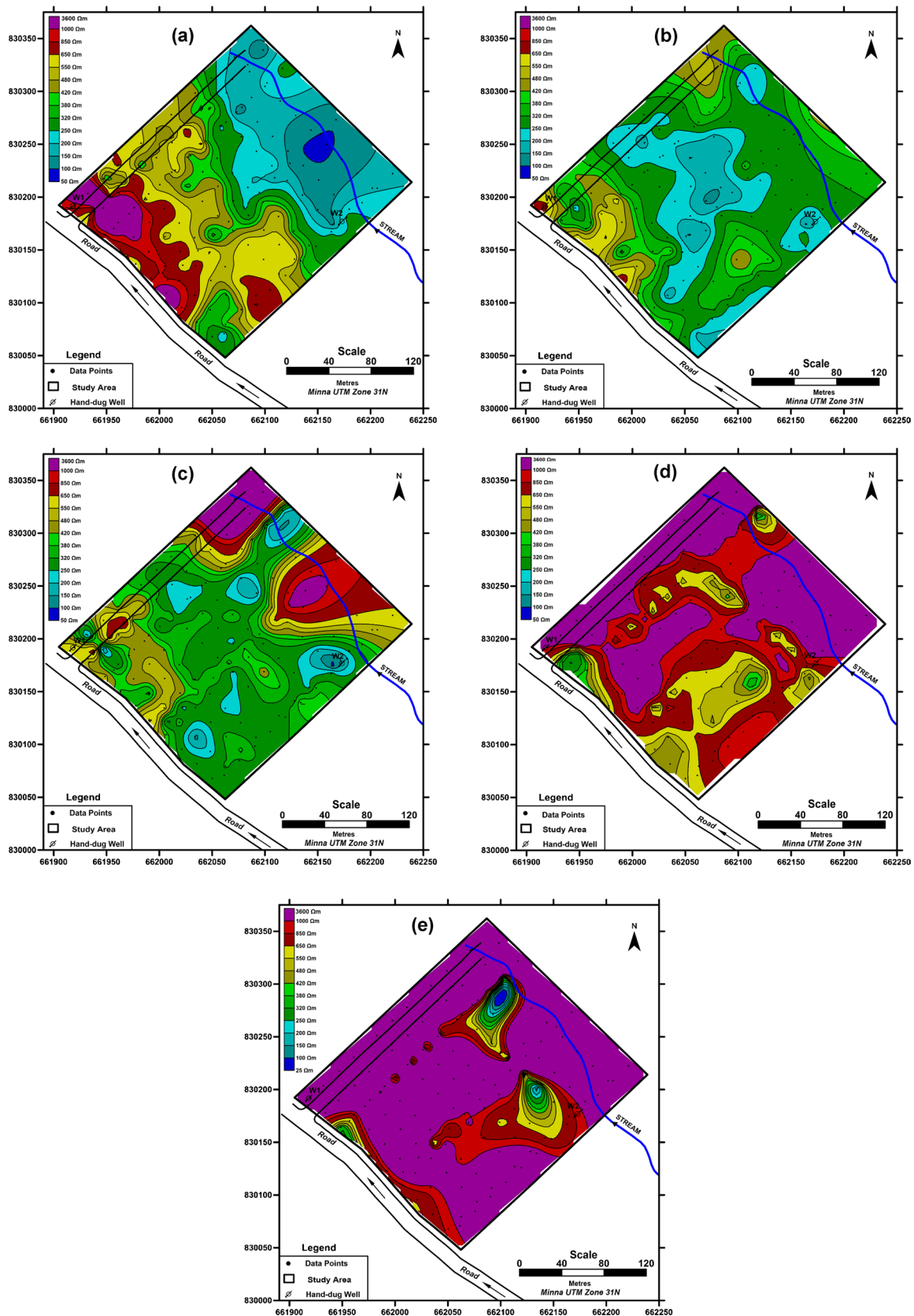
Fig. 4 **a** 0–10-m resistivity depth slice map. **b** 10–20-m resistivity depth slice map. **c** 20–40-m resistivity depth slice map. **d** 40–70-m resistivity depth slice map. **e** 70–100-m resistivity depth slice map

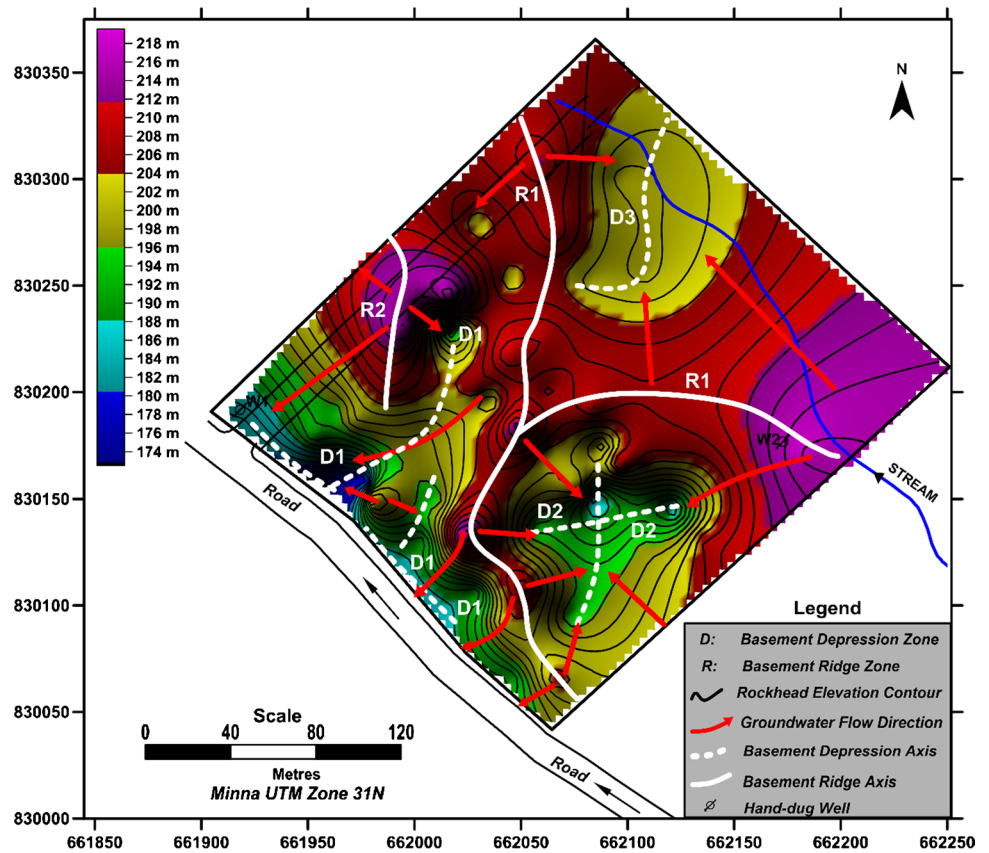**Fig. 5** Basement relief map showing groundwater flow direction

Table 1 Geoelectric characteristic of the study area

Layer No.	Resistivity (Ωm)	Thickness (m)	Layer classification	Composition
1	197–1766	0.3–2.8	Topsoil	Sandy clay/clayey stone concretion/laterite
2	99–800	0.2–6.1	River-fill	Clay/sandy clay/clayey sand
3	319–2003	1.0–14.8	Laterite	Indurated clay
4	166–655	11.9–64.4	Weathered layer	Sandy clay/clayey sand/sand
5	1407 – ∞	*17–69	Fresh basement	Mica schist

* Depth to rock head

installation and protection of utilities (pipes, cables, etc.), and groundwater development.

The geological sequence at the investigated site is composed of the topsoil, fill, laterite, weathered layer, and the fresh basement. The topsoil/fill/laterite in the upper 10 m constitutes the unit within which normal civil engineering structures are usually founded. This horizon with layer resistivity values of < 100 to 3000 Ωm has varying lithologies of clay, sandy clay, clayey sand, stone concretion, and laterite. The engineering competence of the near-surface soils can be semi-quantitatively evaluated based on the layer resistivity values (Table 2) (Idornigie et al. 2006). Based on the referenced table and Fig. 4a, the competence rating varies from moderate around the stream channel to competent and very competent as one moves away from the stream channel. This

Table 2 Subsoil competence rating based on resistivity values in a basement complex region (Idornigie et al. 2006)

Resistivity range (Ωm)	Lithology	Competence rating
< 100	Clay	Incompetent
100–300	Sandy clay	Moderately competent
350–750	Clayey sand/sand	Competent
> 750	Sand/laterite/basement bedrock	Highly competent

site is generally underlain by high-resistivity (> 450 Ωm) lateritic soils (Fig. 2) and adjudged to be competent.

Soil matrix conductivity, the degree of saturation, and concentration (chemistry) of the saturating fluid primarily

determine soil resistivity. Electrically conductive (low resistivity) soils are corrosive as a result of decreased aeration, enhanced electrolyte saturation, and high concentration levels of dissolved salts. The nature of soil in terms of the resistivity value, therefore, determines the degree of corrosivity and hence susceptibility to failure of buried metallic structures such as pipes, cables, and repository tanks as shown by Adeoti et al. (2018). Soil corrosivity can be classified based on resistivity values using Table 3.

Utilities such as pipes, cables, and tanks are embedded at shallow depth, rarely more than 2–4 m below the ground surface. This depth range falls within the geoelectric topsoil/fill/laterite layer, with resistivity range of < 100 to 3000 Ωm (Fig. 3a). The < 100–200 Ωm resistivity zone is within the stream channel with the low resistivity due to high fluid saturation. Except within the stream channel, soil resistivities are generally > 250 Ωm typical of practically non-corrosive soils.

The resistance to current flow of an earth electrode is strongly determined by the resistivity of the soil within which it is buried; hence, soil resistivity measurements are an important parameter when designing earthing installations (Adegboyega and Odeyemi 2011). The lower the resistivity, the fewer are the electrodes required to achieve the appropriate earth resistance (Nagrath and Kothari 2001). Low resistivity (< 100 Ωm), clayey medium, is generally considered as good earthing medium. The subsoil resistivity at depths greater than 1 m within which electrodes can be buried varies from 99 to 1414 Ωm but is generally > 200 Ωm (Fig. 3a) typical of sandy clay, clayey sand, and laterite. These subsoils are fairly good to poor earthing media.

Estimated depths to fresh basement bedrock vary from 17 to 69 m (Fig. 2). The basement bedrock relief map generated from the above depths relative to the surface elevations at the VES station is displayed in Fig. 5 with the groundwater flow directions. The map identifies three major basement depressions (D1–D3) which are groundwater collecting centers and two major basement ridges (R1 and R2) radiating groundwater. The multidirectional groundwater flow pattern typifies the complexity of the basement complex aquifer system (Akanji et al. 2021).

Table 3 Classification of soil corrosivity based on resistivity (Baeckmann and Schwenk 1975; Agunloye 1984; Gopal 2010; British standard BS-1377)

Soil resistivity (Ωm)	Soil corrosivity
< 10	Very strongly corrosive (VSC)
10–30	Very corrosive (VC)
30–60	Moderately corrosive (MC)
60–80	Slightly corrosive (SC)
> 180	Practically non-corrosive (PNC)

The weathered basement constitutes the sole aquifer unit. Except for beneath very few VES stations, there is a sharp gradation between the weathered and the fresh basement. The groundwater yield of a weathered basement aquifer is determined by the degree of shaliness (clay content). Low groundwater yield is encountered when the aquifer unit is clayey. The resistivity type curves of this aquifer unit are the H and KH while their variants include HKH and KHKH types (Olorunfemi and Fasuyi 1993; Oni et al. 2020b).

For the clayey aquifer unit (mica schist weathers into clayey materials (Dijon 1989), the groundwater potential can be evaluated based on the degree of shaliness (clay content) as manifested in variations in layer resistivity values, the aquifer thickness, and possibility of groundwater flow being aided by fractures or pegmatite veins (Mclean and Gribblo 1979). Although the aquifer thickness varies from 11.9 to 64.4 m, it is on the average generally between 20 and 40 m. Mica schist is rarely fractured and so it was not surprising that no fracture was delineated. The aquifer unit can therefore be considered to be moderately thick with layer resistivity values of > 250 Ωm, which makes it slightly sandy.

The recharge of the aquifer through surface precipitation (rainfall) may be low due to the relatively thick and low permeability lateritic overburden and the gently sloping terrain which promotes high surface runoff. There are manifestations of this phenomenon in several erosion channels within the site. There is, however, some prospect of aquifer recharge through base flow from the stream adjoining the northeastern flank, particularly in the low land areas bordering the stream (see Fig. 5) as there are possibilities of outflows from the site too.

The inference from the above is that the groundwater potential within the proposed estate can only be adjudged as of a moderate-level rating.

The threat of groundwater pollution from surface source pollutants such as effluent discharge from numerous privately owned dump sites within the proposed estate will depend on the ability of the overlying layer(s) above the aquifer unit to retard the infiltration of such effluent. That ability will depend on the nature of the soil/subsoil, its thickness and permeability, the depth to water table within the aquifer, the nature of the aquifer itself, and the overall gradient of the terrain.

The overburden for the present site is made up of the topsoil, fill, and laterite. The topsoil/fill is made up of clay, sandy clay, clayey sand, and laterites in places. Both the topsoil and fill overly the lateritic layer with average thickness of < 3.0 m. The underlying laterite is much thicker, averaging more than 7 m (maximum thickness is 14.8 m). It is characterized by relatively high resistivity (up to 3000 Ωm) due to induration and low-porosity/permeability. This layer constitutes the main sealant for infiltrating effluent irrespective of the nature of the topsoil (which in

most places is lateritic) and the fill. The zone of partial saturation (very rarely do we have complete dryness in a weathered basement) would also act as a natural filter for incoming pollutant.

The terrain generally slopes from the southwest towards the northeast along the stream channel. For this reason, the water table is lower at 10 m beneath well W1 at the northwest than at 3.3 m beneath well W2 at the southeast. This makes the threat of groundwater pollution higher in the area around the stream channel than in the upland.

Conclusions

The study concludes as follows that

(i) Five subsurface layers consisting of the topsoil, fill, laterite, weathered basement, and fresh basement were delineated within the study area. The weathered basement forms the main aquifer with thicknesses ranging from 11.9 to 64.4 m but averaging between 20 and 40 m. Groundwater development is feasible through moderately deep to deep (optimum of 70 m) with prospect for moderate groundwater yield.

(ii) The subsoil in the upper 10 m within which civil engineering structures are generally founded is lateritic and rated, based on resistivity values (generally > 450 Ωm), as moderate to highly competent with very low risk of foundation failure due to subsoil settlement.

(iii) The significantly thick (average of > 7 m) low-porosity/permeability lateritic layer overlying the weathered layer aquifer constitutes a sealant against infiltrating pollutant with the groundwater significantly protected.

(iv) Except within the stream channel, soil/subsoil resistivity values are generally > 250 Ωm typical of practically non-corrosive soils. Buried metallic structures within the proposed estate are at extremely low risk of being corroded. However, based on the relatively high subsoil resistivities, the subsoils are poor to fairly good earthing media. There could be necessity for additives such as charcoal or salt to enhance electric conductivity, most especially at localities with very resistive lateritic soils.

Declarations

Conflict of interest
The authors declare no competing interests.

References

Adegoyega GA, Odeyemi KO (2011) Assessment of soil resistivity on grounding of electrical systems: a case study of North-East Zone, Nigeria. J Acad Appl Sci 1(3):28–38

Adenika CI, Ariyibi EA, Awoyemi MO, Adebayo AS, Dasho OA, Olagunjo EO (2018) Application of geotechnical approach to highway pavement failure: a case study from basement complex terrain Southwestern Nigeria. Int J Geo-Engineering 98. https://doi.org/10.1186/s40703-018-0076-0

Adeoti L, Adegbola RB, Ademilola JA, Oyediran TA (2018) Soil resistivity measurement for corrosivity assessment using Barnes method. Nigeria Res J Eng Environ Sci 3(2):703–712

Agunloye O (1984) Soil aggressivity along steel pipeline route at Ajaokuta. J Min Geol 21(12):97–101

Ajayi LA (1987) Thought on road failure in Nigeria. Nig Eng 22(1):10–17

Akanji AA, Oni AG, Olorunfemi MO (2021) Groundwater prospectivity assessment of a field of hand-dug wells in the area around the Murtala Muhammed postgraduate hall OAU, Ile-Ife, using geoelectric parametric soundings. Pac J Sci Tech 22(1):274–284

Akintorinwa OJ, Ojo JS, Olorunfemi MO (2011) Appraisal of the causes of pavement failure along the ilesha – Akure highway, Southwestern Nigeria using remotely sensed and geotechnical data. Ife J Sci 13(1):185–198

Baeckmann WV, Schwenk W (1975) Handbook of cathodic protection: the theory and practice of electrochemical corrosion protection techniques. Protcullis, Survey, p 396

Bayowa OG, Adagunodo TA, Adewoyin OO (2019) Geoelectric investigation of foundation failure in Akowonjo, Ogbomoso, Nigeria. IOP Conference Series: Earth and Environmental Science 331(2019). 012065: 1–10

BS-1377 (1990) Methods of tests for soils in civil engineering properties. British Standard Institute, London

Dijon RE (1989) Groundwater exploration and development in Precambrian crystalline basement areas of African. The main issues. In: Groundwater exploration and development in crystalline basement aquifers, Proceeding, the Zimbabwe 1(1–5), Commonwealth Science Council, Pall, Mall, London. pp 32–38

Eluwole AB, Olorunfemi MO (2012) Time-lapsed geophysical investigation of the Mokuro earth dam embarkment Southwestern Nigeria for anomalous seepages. Pac J Sci Tech 13(1):700–712

Environmental Impact Assessment (EIA) (1992) Act Cap 86. Federal Environmental Protection Agency, Lagos

Fatoba JO, Olorunfemi MO, Eluwole AB (2015) Subsurface structures and the effect on flexible pavement performance: the Shagamu-Benin expressway Southwestern Nigeria as case study. Indian J Geosci 69(2):137–144

Federal Ministry of Environment (FMENV) (1995) Environmental impact assessment procedural guidelines, Abuja, Nigeria

Geological Survey of Nigeria (1974) Iwo sheet 60, 1:25,000 geological map. Published by the Authority of the Federal Republic of Nigeria

Giza II, Igwe O (2018) Assessment of foundation instability using integrated geotechnical and geophysical techniques. A case study of Giza, Keana LGA, Nasarawa State, North Central Nigeria. ASRJETS 41(1):85–108

Gopal M (2010) Corrosion potential assessment, the geology of part of Southwestern Nigeria. Geological Survey of Nigeria, pp 31–87

Idornigie AI, Olorunfemi MO, Omitogun AA (2006) Electrical resistivity determination of subsurface layers, Subsoil competence and soil corrosivity at an engineering site location in Akungba – Akoko, Southwestern Nigeria. Ife J Sci 8(2):139–177

Kearey P, Brooks M, Hill I (2002) An introduction to geophysical exploration (third edition). Blackwell Publishing, Malden, USA, p p281

Keftin NA, Anigbogu AN, Yusuf MI (2009) An assessment of compliance of building construction projects with environmental impact assessment requirements in Nigeria. FUTY J Environ 4(1):36–44

McLean AC, Gribblo CD (1979) Geology for civil engineers. George Aken and Uniwin Publication

Momoh LO, Akintorinwa O, Olorunfemi MO (2008) Geophysical investigation of highway failure – a case study from Basement Complex Terrain of Southwestern Nigeria. J Appl Sci Res 4(6):637–648

Nagrath IJ, Kothari D (2001) Power System Engineering. Tata McGraw-Hill Publishing Company Limited, New Delhi

Oladapo MI, Olorunfemi MO, Ojo JS (2008) Geophysical investigation of road failure in the basement complex terrain of Southwestern Nigeria. J Appl Sci Res 3(2):103–112

Oladunjoye MA, Adefehinti A, Akinrinola OR (2021) Integrated geophysical investigation for the characterisation of valley bottom soil at Ilora, southwestern Nigeria. NRIAG J Astron Geophys 10(1):110–124. https://doi.org/10.1080/20909977.2020.1859668

Olorunfemi MO, Fasuyi SA (1993) Aquifer types and the geoelectric/hydrogeologic characteristics of part of the central basement terrain of Nigeria (Niger State). J Afr Earth Sc 16(3):309–317

Olorunfemi MO, Ojo JS, Sonuga FA, Ajayi O, Oladapo MI (2000) Geoelectric and electromagnetic investigation of failed Koza and Nassarawa Earth dams around Katsina, Northern Nigeria. J Min Geol 36(1):51–65

Olorunfemi MO, Idornigie AI, Coker AT, Babadiya GE (2004) On the application of the electrical resistivity methods in foundation failure investigation – a case study. Global J Geophys Sci 2(1):139–151

Olorunfemi MO, Ojo JS, Idornigie AI, Oyetoran WE (2005) Geophysical investigation of structure failure at a factory site in Asaba area, Southern Nigeria. J Min Geol 41(1):111–121

Olorunfemi MO, Oni AG, Fadare TK, Olajuyigbe OE (2021) On the application of the magnetic method in the mapping of mineralized pegmatites in mica schist underlain basement complex of southwest Nigeria. Pac J Sci Technol 22(2):295–306

Oni AG, Olorunfemi MO (2016) Integrated geophysical investigation of the Igbara-Oke-Igbara-odo road pavement failure in Ondo/Ekiti State, Southern Nigeria. Ife J Sci 18(1):199–131

Oni AG, Eniola PJ, Olorunfemi MO, Okunubi MO, Osotuyi GA (2020a) The magnetic method as a tool in groundwater investigation in basement complex terrain: Modomo Southwestern Nigeria as a case study. Appl Water Sci 10(8):1–18

Oni AG, Adediran AA, Olorunfemi MO, Eniola PJ, Adewale EA (2020b) Evaluation of the groundwater potential Modomo community in Ile-Ife, Southwest Nigeria, using integrated geophysical techniques. Sustainable Water Recourses Manage 6(6):1–18

Sangodiji EE, Olorunfemi MO (2013) Geophysical investigation of a suspected foundation failure at Ogbomoso, Southwestern Nigeria. Pac J Sci Tech 14(2):522–536

Telford WM, Geldart LP, Sheriff RE (1991) Applied geophysics (second edition). Cambridge University Press, Cambridge, p p786

Turner DC (1983) Upper Protozoic schist belts in the Nigerian sector of the Pan-african Province of West Africa. Precambrian Res 21:55–79