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Canal structure subsidence investigation using ground penetrating radar and geotechnical techniques

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article

Abstract

Channel structure settlement along a canal in Lagos, southwestern Nigeria, was investigated using the ground penetrating radar (GPR) and geotechnical techniques with a view to establishing the cause(s) of the structure failure. GPR probing was carried out along eight parallel traverses in the E–W direction using the GSSI SIR-3000 200 MHz monostatic antenna. Geotechnical investigations involving sieve analysis, Atterberg limits, moisture content, organic content and consolidation test were carried out for soil classification and competence test. X-ray diffraction (XRD) studies were conducted to determine clay mineralogy of the peaty soil. The GPR data were processed using Radpro software. Four lithological layers consisting the topsoil (sand), peat, clay and sandy clay were delineated from the processed GPR data. Peat occurred at shallow depth to depths deeper than the foundation depth of the engineering structure investigated. The geotechnical results revealed that the peat has 125–167 % moisture content, high liquid limit and plastic index values of 109–174 % and 60–100 % respectively and organic content of 5.12 %. The sieve analysis showed that the peaty soil is fine grained having up to 98 % passing at 0.004 mm sieve opening exhibiting high compressibility and low consolidation coefficients. This peat was classified as organic clay with peat using the unified soil classification system. The XRD analyses showed the dominance of kaolinite, illite and quartz minerals in the peaty soil. This study revealed that the peaty soil underlying the investigated area has geologic and engineering properties not suitable to sustain the canal construction.

Keywords: Peaty soil, Settlement, Subsidence, Consolidation coefficient, Compressibility

Background

Ground subsidence and settlement have posed great challenges to engineering structures, in some cases, resulting in moderate to severe damage. The high rate of buildings and infrastructural failures in Nigeria especially in Lagos area which always involve loss of lives and properties in recent times calls for diverse subsurface investigation that could aid in engineering design to forestall such failures (Adepelumi and Fayemi [1]; Evinemi [2]). Many engineering structures in Lagos especially those at the coastal areas are faced with settlement problem. This has taken an alarming dimension that requires urgent attention. Hence necessitating site characterization using geotechnical and

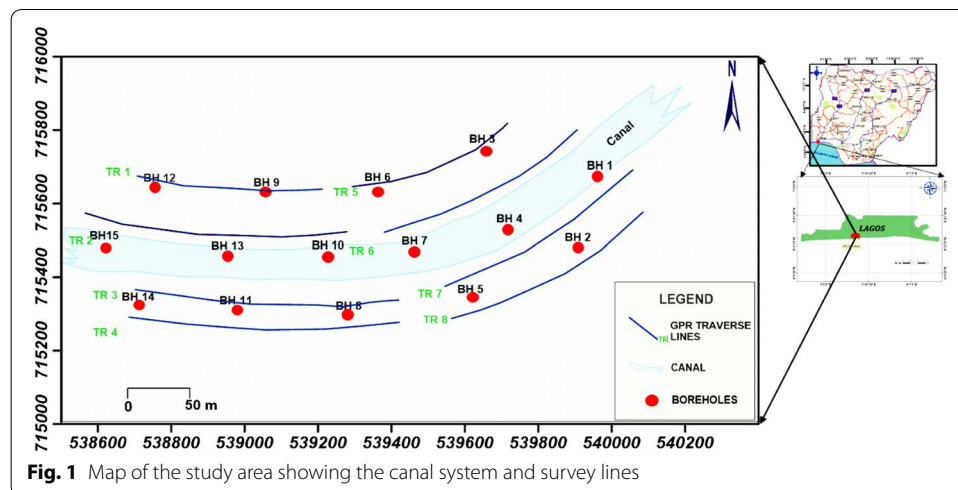
geophysical methods for structural engineering purposes before further constructions are carried out in these areas.

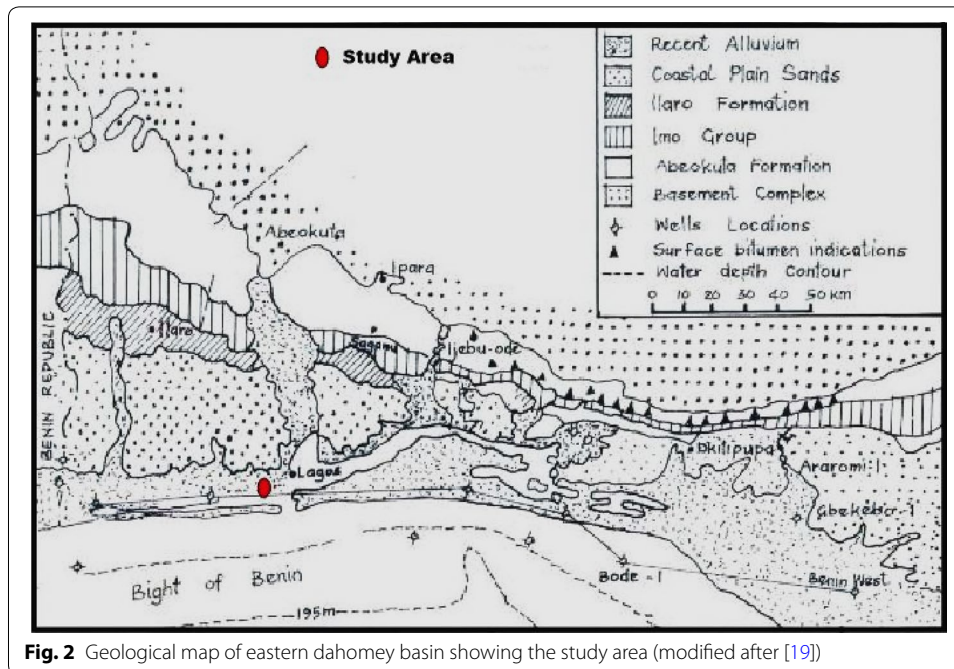
Ground penetrating radar is a subsurface imaging method that provides high-resolution in formation to a depth of typically 0–10 m, although depths up to 40 m [3–5] are possible in some geological environments. This penetration depth is limited by the transmitted power. They use high voltage (up to 1000 V impulses) and low frequency (25–50 MHz antennae), which can reach up to 40 m depth in low conductivity ground conditions. Future GPR systems will deploy a new generation of UWB current-driven antenna, rather than voltage-driven antenna [6]. The GPR system comprises an antenna which emits electromagnetic energy, and receiver which receives the reflected energy from the surfaces as well as that from the inner subsurface. The reflected energy depends majorly upon the type and nature (frequency) of the antenna, and the nature of materials involved. The energy reflected is transformed into visual images, which provide extensive data on the sub-surface (inner) materials, when interpreted properly.

The applications GPR are very varied and include the location of buried services, the detection of voids or cavities, mapping bedrock depth or faults and fracture zones in rock. Other applications include locating steel reinforcing in concrete, geotechnical foundation investigations, archaeological, environmental and hydrogeological surveys [6].

Geological setting

The study area is located within Lagos State, southwestern Nigeria. It lies between latitudes 715000 N and 716000 N and longitudes 538600 E and 540300 E of the universal traverse mercator (Fig. 1). It covers a geographical area of approximately 500² m The topography is generally flat with localized undulations due to sand heaps from canal dredging and sand filling activities in the area. The area belongs to Dahomey Basin which is also known as Dahomey Embayment or Benin Basin or as West Nigerian Basin. It extends from southeastern Ghana in the West, through Southern Togo and southern Benin Republic (formerly Dahomey) to southwest Nigeria (Fig. 2).





The axis of the basin and the thickest sediments occur slightly west of the border between Nigeria and Benin Republic. The basin is bounded on the west by faults and other tectonic structures. Its eastern limit is marked by the Benin Hinge line, a major fault structure marking the western limit of the Niger delta basin. To the west of the Benin Hinge line is the Okitipupa Ridge [7]. The Tertiary sediments of the Dahomey basin thin out and are partially cut off from the sediments of the Nigeria delta basin against this ridge of basement rocks [8]. The basin's offshore limit is not well defined.

Thus, the area investigated is situated in the southern part of Dahomey basin and consist series of stratified sedimentary sequence made up of silt clay, peat and sand. The site also forms part of a sub-littoral environment created by meandering rivers that have been reclaimed by sand filling and human activities.

Basically, the subsoil of the project area is made up of the so called flood plain sands, which are represented by sandy clay, peat with clay intercalation, clay and clayey sand. On relatively higher grounds, materials exposed have been leached into lateritic red earth with moderate strength. On the other hands, the low lying areas and old water courses give rise to predominantly stagnant water in which accumulation of decayed vegetation would have taken place in geological past resulting in peat and soft organic clay formation at surface and to some depth.

Methods

The research methodology adopted involve geophysical, geotechnical and laboratory investigations. GPR method was employed for the geophysical survey. The GPR survey was carried out along eight parallel traverses each 500 m long and trending in approximately E-W direction using an USA manufactured GSSI SIR System-300 equipment. The survey was done using a 200 MHz monostatic shielded antenna oriented parallel

to the survey direction (parallel-broadside) in continuous collection mode. The antenna was preset with three gain points in order to improve the scans during data acquisition while 33 scans per meter were taken (representing 3 cm station spacing) with a sampling window of 400 ns with offset of +25 ns. A 16-fold stack was used for the traces during data recording to improve the signal to noise (S/N) ratio of the data. The GPR data positioning was calibrated using a survey wheel (odometer) and each radar trace contains 1024 points per trace. The SIR-system and antenna were pulled manually on land during data collection.

The data collected were processed using the GPR processing flow contained in the RADPROFwin software to produce 2D radargram of the subsurface formation delineated which was studied and interpreted for possible structural deformations such as microfaults, fractures, voids/cavity and weak zones and identification of subsurface lithologies. The basic processing steps used in this work include: Data editing, DC filtering, dewowing, time-zero-drift correction, automatic gain control, smoothing by 2-D median filtering, and hilbert transformation. Advanced processing steps that were applied to the radar images include; predictive deconvolution, velocity spectrum analysis and attribute analysis [9], Adepelumi and Fayemi [1]; Adepelumi et al. [10].

The geotechnical investigation involve obtaining soil samples from drilled boreholes at various locations within the study area for the determination of their engineering properties such as sieve analysis, natural moisture content, Atterberg limits, bulk density, specific gravity, organic content of soil etc. X-ray diffraction (XRD) analytical tool was also used for the determination of the clay mineralogical investigations of the collected soil samples.

Results and discussions

Ground penetrating radar is a method that is commonly used for civil engineering-geotechnical, geological, environmental, archeological and other shallow investigations (1–40 m). For over 30 years, GPR has been used extensively for hydrogeological investigations and civil engineering investigations [11].

Permittivity to a great extent and conductivity and radar wave frequency to a lesser extent controlled the velocity of EM waves through the ground (or a material). For near surface materials, the phase velocity, V_{ph} , and attenuation coefficient may be expressed as [12]; Santamarina et al. [13, 14].

$$V_{ph} = \frac{C_0}{\sqrt{\frac{\kappa'}{2} \left(\sqrt{1 + \left(\frac{\sigma_{eff}}{\kappa' \epsilon_0 \omega} \right)^2} + 1 \right)}} \quad (1)$$

$$\alpha = \frac{\omega}{C_0} \sqrt{\frac{\kappa'}{2} \left(\sqrt{1 + \left(\frac{\sigma + \kappa'' \epsilon_0 \omega}{\kappa' \epsilon_0 \omega} \right)^2} - 1 \right)} \quad (2)$$

where σ is the DC-electrical conductivity, κ' and κ'' are the real and imaginary components of relative dielectric permittivity, $\epsilon_0 = 8.85 \times 10^{-12}$ F/m is the dielectric permittivity of the free space, $c_0 = 2.999 \times 10^8$ m/s is the electromagnetic (EM) wave velocity of

the free space, and ω is the angular frequency. The conductivity σ also affects the depth of penetration, which is commonly represented by the skin depth, S_d .

$$S_d = \frac{1}{\alpha} = \frac{C_0}{\omega \sqrt{\frac{k'}{2} \left(\sqrt{1 + \left(\frac{\sigma + \kappa'' \epsilon_0 \omega}{\epsilon_0 \omega k'} \right)^2} - 1 \right)}} \quad (3)$$

The skin depth decreases as the angular frequency and the effective electrical conductivity increase. However, the real depth of penetration of the electromagnetic wave depends not only on the properties of the subsurface materials but also on the characteristics of the GPR system and the quality of the reflector [11, 15, 16]. The skin depth calculated from the GPR results should be considered as a lower bound on the real penetration depth. In peat material, GPR works relatively well because the low electrical conductivity allows large penetration depth and the changes in bulk density within the peat and with respect to the mineral sediment provide strong reflections for excellent geophysical imaging. Peat usually overlies layers with much lower resistivity and water content like clay, silt or weathered bed rock.

Estimated velocities electromagnetic waves of some of the materials encountered in the study area as gotten from literatures are shown in table below Table 1.

In the case of this study, average velocity of the major materials (sand, peat and sandy clay) were used to determine the skin depth of the EM wave of which up to 14 m was probed as shown in Figs. 3 and 4.

Thus, results of the derived GPR radargrams showing the various subsurface layers delineated and their interpretation with respect to the likely cause of structure settlement experienced in this area are discussed. Also, borehole logs and subsurface stratigraphic study of some drilled boreholes in the area and geotechnical investigations involving laboratory soil classification test, oedometer consolidation test of some recovered soil samples and their x-ray diffraction analysis results are also presented.

Interpretation of ground penetrating radar (GPR) records

Eight radar traverses were taken and processed across the study area. Four major stratigraphic layers were delineated from the processed GPR radargrams. These are interpreted as topsoil (that is made up of predominantly sand), underlain by peat with clay intercalation, then clay and sandy clay. The peat having a low amplitude extends across all the sections with thickness ranging between 3.8 and 6.0 m. Using an average velocity of 0.145 m/

Table 1 GPR velocity table and analysis of velocity, dielectric constants, attenuation, and conductivity values for materials from various sources

Material	Dielectric constant	Conductivity (mS/m)	GPR velocity (m/ns)	Attenuation (dB/m)
Air	1	0	0.3	
Clay (saturated fresh water)	8–12		0.09–0.11	
Clay (wet)	8–12	100–1000	0.106–0.087	
Organic soils			0.04	
Peats			0.04	
Sand and clays (wet)	9–67		0.04–0.10	

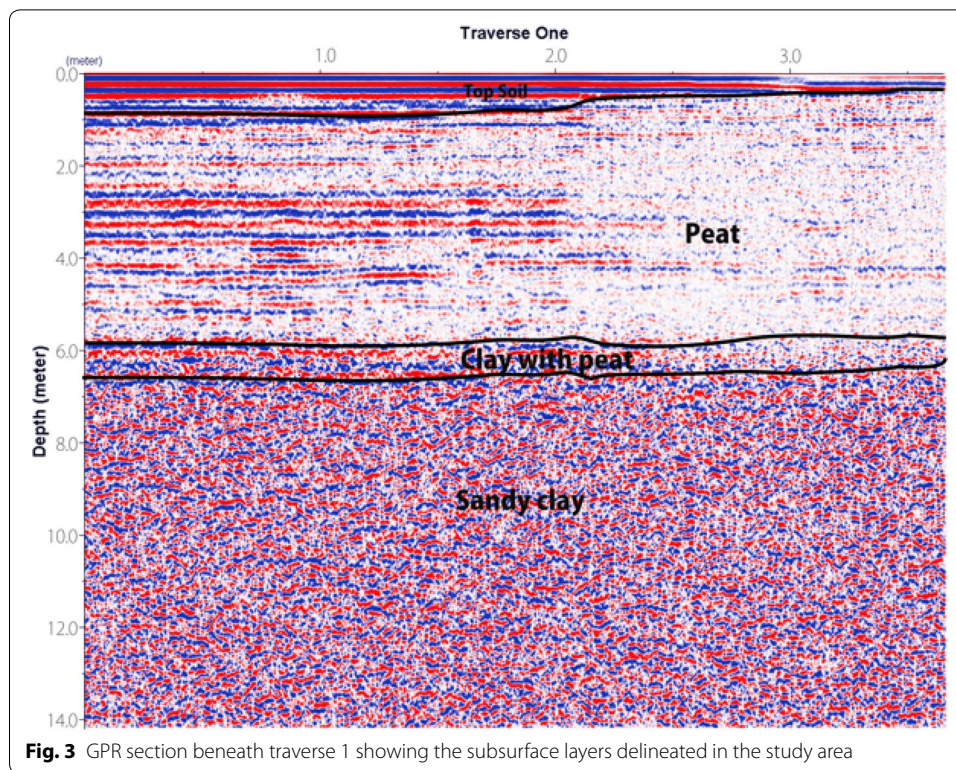
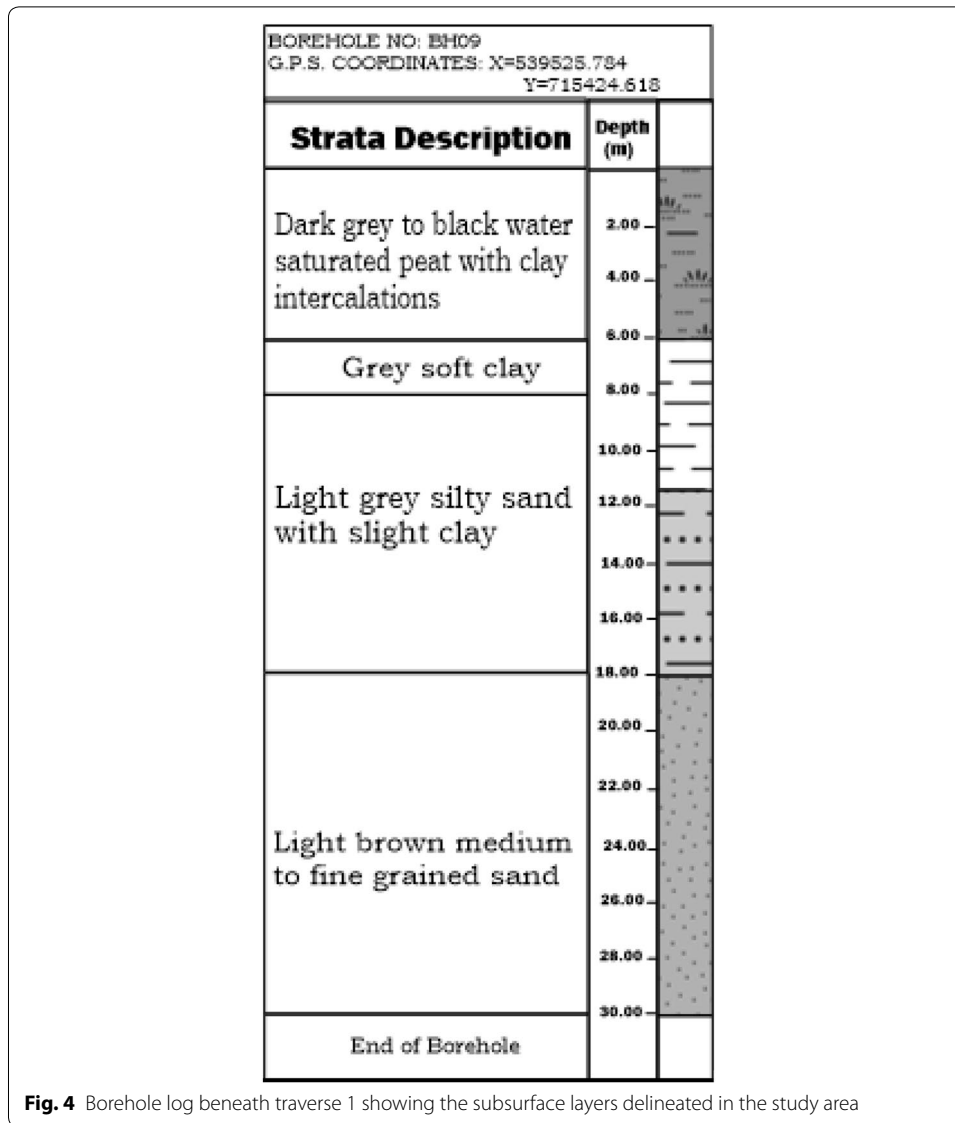


Fig. 3 GPR section beneath traverse 1 showing the subsurface layers delineated in the study area

ns [18], the depth to the peat was found to range from 0.5 to 6.0 m within the study area. In some places within the study area, the peat occurs right from the ground surface but where they do not, they are overlain by a planar, high reflection/amplitude pattern top layer of about 0.5 m in thickness (Fig. 3). It is worthy of note that this top layer is not indicated in almost all the borehole log data used probably because of its small thickness and the high degree of peat infiltration into it. The top layer however has high amplitude, discontinuous, chaotic, alternating high and low reflection which stands out very conspicuous from the underlining layer (peat) which is hummocky with micro-scale diffraction. Though the peat layer from the GPR radargram correlates with what from the borehole log referred to as water saturated peat with clay intercalation (Figs. 3 and 4), its thickness and/or depth extent differs greatly from that obtained from the borehole logs. The third layer which underlain the peat is a discontinuous, hummocky layer and the reflection amplitude alternate between both high and low but stand out from adjacent layers as well. This layer has a depth ranging from 5.8 to 7.2 m across the GPR profiles. Thus, this layer is interpreted as a clay formation with peat infusion. The last layer delineated from the GPR profiles is the massive, high amplitude, discontinuous micro-scale diffraction layer which has a higher thickness (>8 m) than the other layers as delineated from the GPR radargram. Based on both literature and borehole log description, this layer is interpreted as being made up of sandy clay or silty sand. It is deduced that, all of these sediments are recent along this flood plain, and probably have not undergone much geological processes (Figs. 5 and 6).

Attempts were made to correlate two of the borehole logs with the radar profile by overlying the log on the GPR section. Thus, borehole 09 which falls within GPR profile Traverse one and borehole 07 that falls within GPR profile three were correlated to see if



the layers delineated from the radar profiles matched up with that from the log description from the boreholes (Figs. 7 and 8). The log description to 18 and 20 m depth for boreholes 07 and 09 respectively are:

Borehole 09

- 0.00–6.00 m—dark grey to black water saturated peat with clay intercalations.
- 6.00–11.50 m—grey soft clay.
- 8.00–18.00 m—light grey silty sand.

Borehole 07

- 0.00–6.00 m—brownish grey watery peat.
- 6.00–9.00 m—light grey clayey silty sand occasionally coarse.
- 9.00–20.00 m—light grey silty sand.

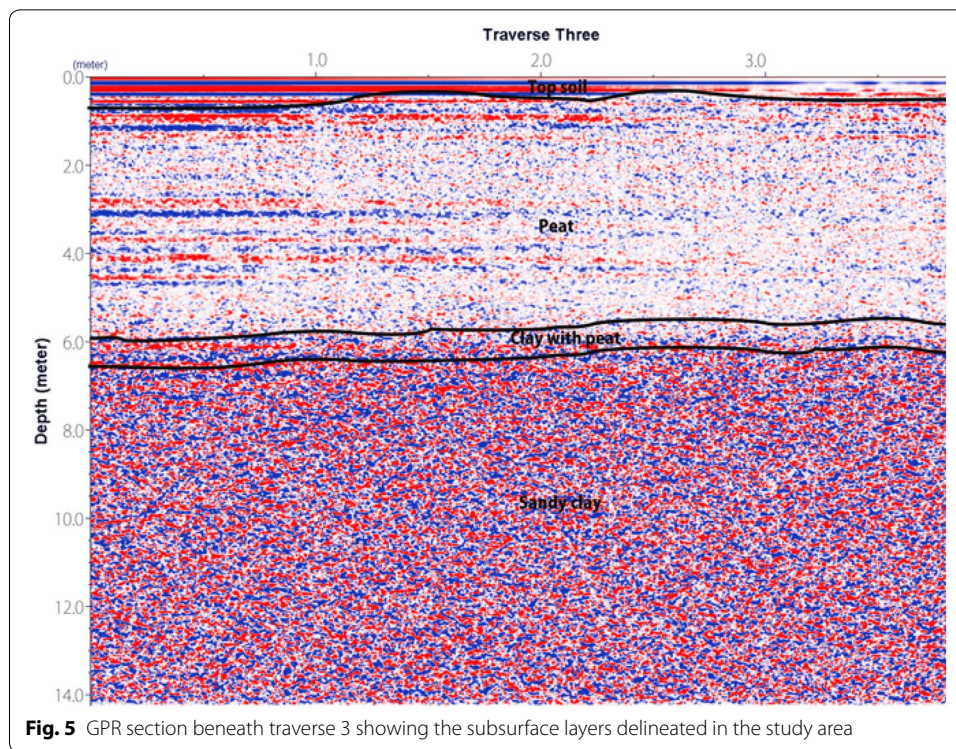


Fig. 5 GPR section beneath traverse 3 showing the subsurface layers delineated in the study area

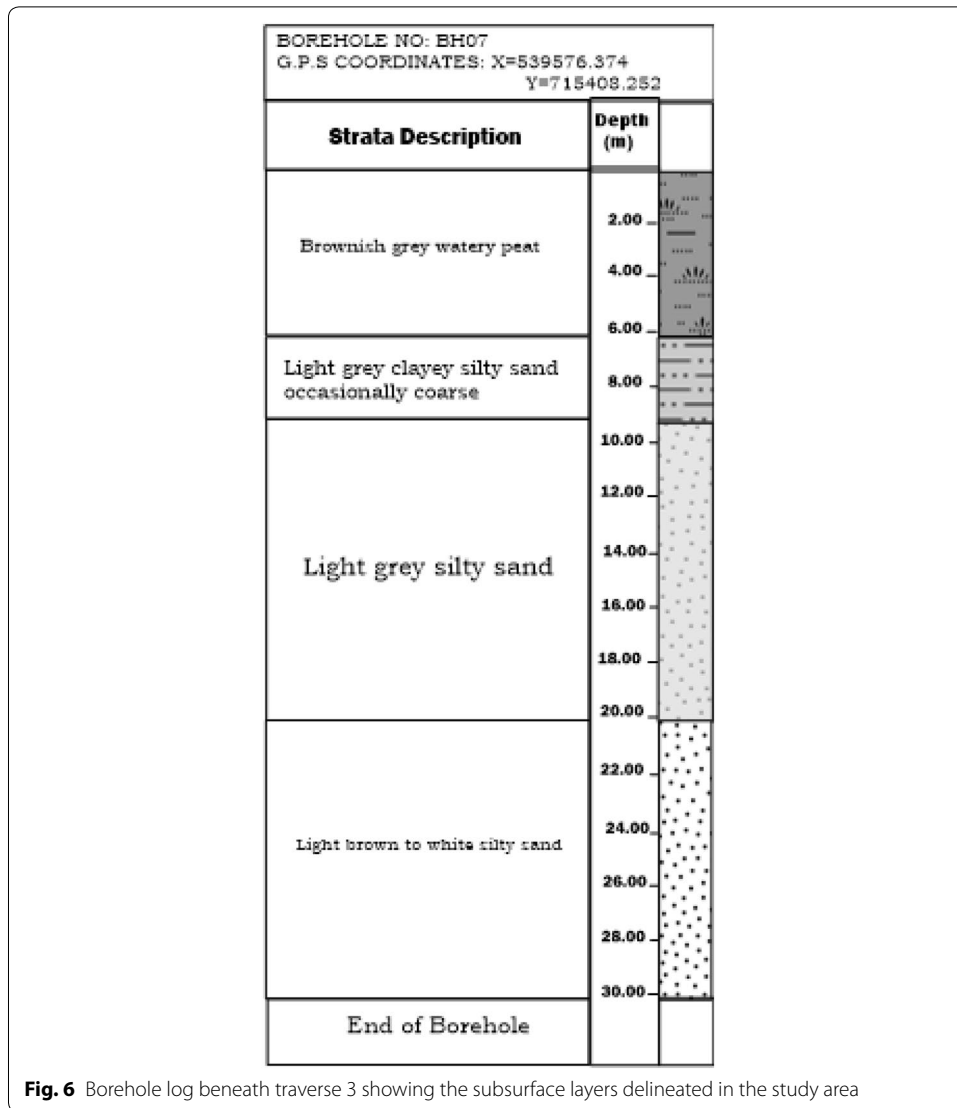
Thus, similar lithologies were observed from the GPR radar profile of Traverse one and three respectively (Figs. 7 and 8) except that the thin sandy clay top soil which were delineated in the GPR profiles were not taken into account in the descriptive logs from the borehole data. A significant difference was observed to occur between the thicknesses of the layers delineated from the GPR profiles compared to from the borehole logs.

Geotechnical investigation of the study area

In order to understand the engineering properties of soil in the study area; some detailed sub-soil investigation involving drilling and geotechnical analysis which involve laboratory soil classification tests of some soil samples were carried out. Borehole log description, laboratory soil classification tests and oedometer consolidation test were attempted and are as shown in the sections below.

Sub-soil sequence

The detailed logs of the sub-soil sequence of four out of the 15 drill locations at the project site which also fall within the area probed using GPR are presented in Fig. 9. Generally, the sub-soil sequence varies in depth and sometimes in lithologies at some of the locations investigated. Variation in thickness of strata and some lithological variation across the study area was observed. The top layer delineated by the GPR survey was not shown in any of these borehole logs probably due to the thin thickness of this top layer (about 0.5 m), it is classified as the same lithology with the peat during logging except at few boreholes far away from the GPR survey area where this top layer is taken into account. Subsequent layers are made up of greyish clayey sand, clay and or light grey silty sand with clay. Figure 9 shows a 6.0 m peat layer as compared to the 4.0, 6.0 and 9.5 m

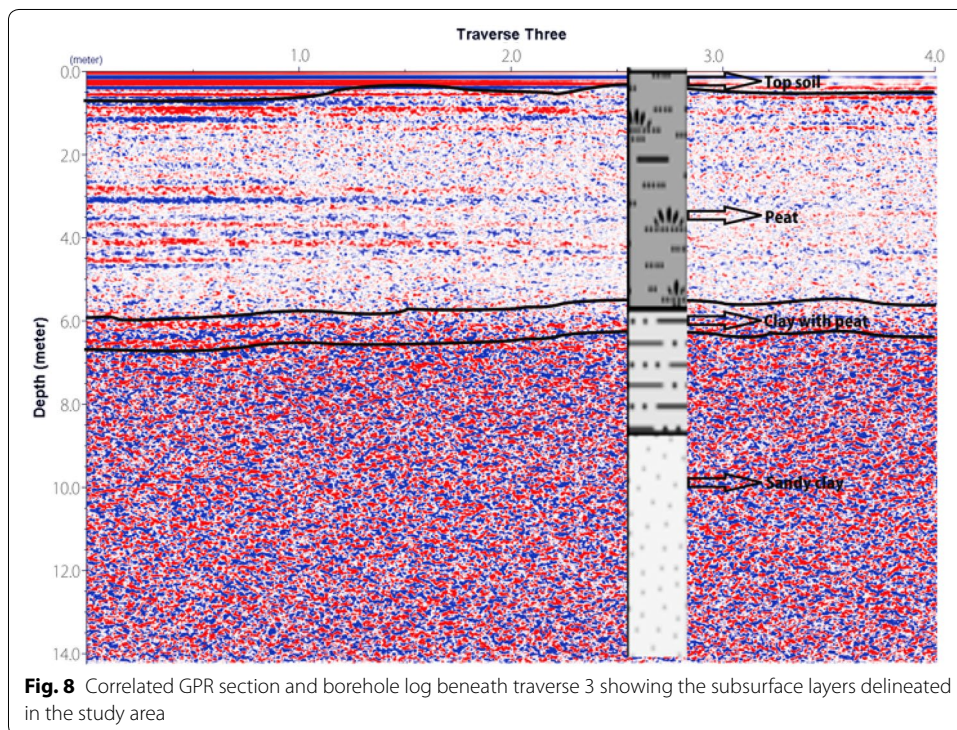
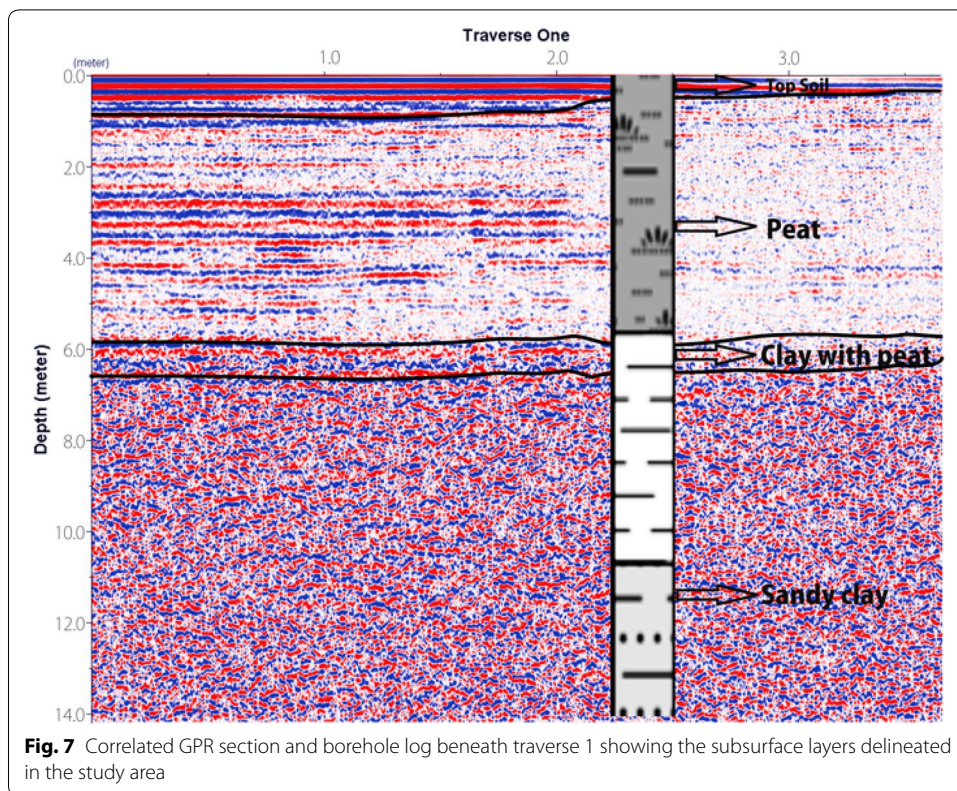


peat layer observed in the boreholes 09, 10, 07 and 15 respectively. It was observed, that the canal structure foundation which is just 2 m depth is laid on the highly incompetent peat layer across the area.

Laboratory soil classifications

Also, results obtained from the geotechnical technique involving sieve analysis, Atterberg limits, natural moisture content, organic content, specific gravity, bulk density, and oedometer consolidation tests share many similarity with that of the GPR result. Lithologies identified from borehole logs are virtually the same with those delineated from the GPR sections. Though the GPR does not probe to the depth penetrated by the borehole (30 m), but it correlated fairly to the GPR depth extent of about 14 m.

The soil classification tests showed that the topsoil and peat layer are highly saturated with water. Bulk density increases with depth with the first 6 m depth having a bulk density between 1.03 and 1.27. Meanwhile, high liquid limit (LL) and plastic index (PI) are



observed at between 4 and 6 m depth across the study area (Table 2). An indication also attesting to the fact that the soil has high degree of water saturation and the presence of clay respectively. Based on the unified soil classification (UCS), the subsurface materials of

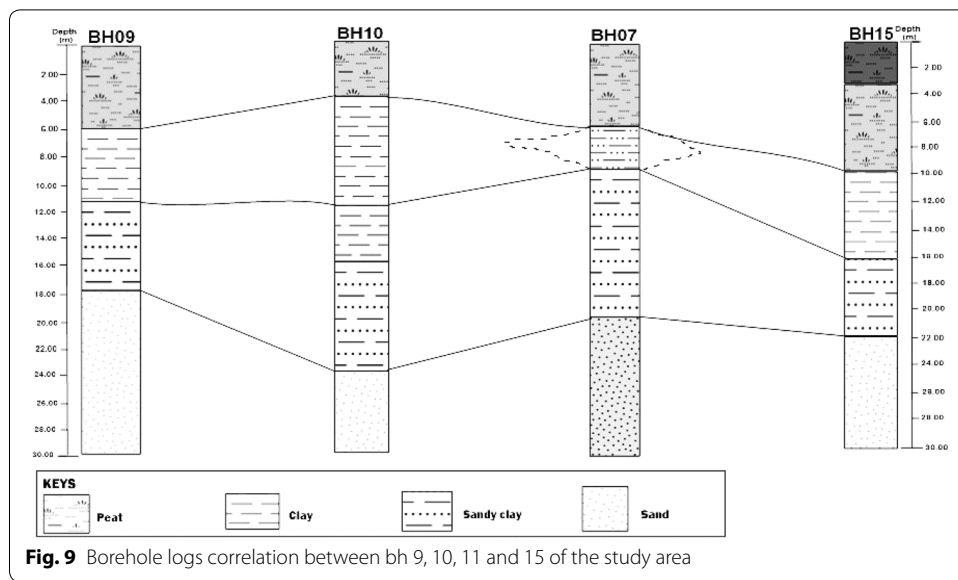


Table 2 Atterberg limits values of bh 09, 10, 07, and 15

BH NO.	Sampling depth (m)	LL	PL	PI
BH 09	0.00–6.00	127	58	69
BH 10	0.00–4.00	107	47	60
BH 07	0.00–4.00	109	49	60
BH 15	0.00–7.00	174	74	100

this study area are classified into organic clay with peat (OH-Pt), organic clay (OH), sandy clay (SC) and silty sand (SM). The oedometer consolidation test shows that the peaty soil has high compressibility (M_v) and low consolidation (C_v) (Table 3). While coefficient compressibility decrease downward, the coefficient consolidation increases downward showing a poor foundation material at the shallow section (Raju et al. [17, 18]). It could therefore be inferred from this result that a better foundation material probably lies at depth.

X-Ray diffraction results

X-ray diffraction analyses carried out on some of the peaty soil samples of the study area showed the dominance of kaolinite, illite and quartz with a stain of vermiculite (in one of the samples) and are summarized in Table 4 below.

The XRD result of the study area indicates that the dominant minerals at BD_B and BD_D are kaolinite, illite, and quartz in that order, while at BD_A and BD_C, it is illite, kaolinite and quartz. Little quantity of vermiculite was observed in just one sample area (BD_D). It is pertinent to note that when clay soils are combined with sufficient water irrespective of the type of clay, they can become very effective lubricants and when a sufficient quantity of clay is intermixed with the coarser granular portion of soil, lubrication will develop whenever enough water is added. As the ability of soils to resist deformation depends very largely on the internal friction, wet clay has the effect of reducing or cancelling out the frictional resistance [20]. The three major clay minerals that are expedient

Table 3 Summary of oedometer consolidation test result

Sample no.	Depth (m)	Bulk density (Mg/m ³)	Pressure range (KN)	Compressibility Mv (m ² /MN)	Consolidation Cv (m ² /yr)
BH 09	3.00	1.03	50–100	2.884	0.16
			100–200	2.872	0.15
			200–400	2.855	0.14
			400–800	2.818	0.14
	9.00	1.06	50–100	0.765	1.9
			100–200	0.750	1.9
			200–400	0.734	1.7
			400–800	0.706	1.9
BH 10	3.00	1.20	500–100	2.745	0.16
			100–200	2.721	0.15
			200–400	2.689	0.14
			400–800	2.654	0.14
	8.00	1.36	50–100	0.562	1.7
			100–200	0.532	1.6
			200–400	0.512	1.5
			400–800	0.501	1.6
	13.50	2.02	50–100	0.155	2.4
			100–200	0.130	2.4
			200–400	0.117	2.5
			400–800	0.095	2.4
BH 07	2.00	1.21	50–100	2.586	0.15
			100–200	2.572	0.12
			200–400	2.550	0.12
			400–800	2.520	0.14
	5.00	1.59	50–100	2.275	0.14
			100–200	2.262	0.15
			200–400	2.245	0.14
			400–800	2.230	0.14
BH 15	6.00	1.11	50–100	2.767	0.15
			100–200	2.734	0.13
			200–400	2.714	0.13
			400–800	2.700	0.14
	12.00	1.89	50–100	0.565	1.8
			100–200	0.551	1.8
			200–400	0.532	1.7
			400–800	0.506	1.9

Table 4 General characteristics and minerals observed by XRD analysis in study area

Sample name	General characteristics	Main mineral observed
BD_A	Depth-1 m	Illite, quartz and kaolinite
BD_B	Depth-1 m	Kaolinite, illite and quartz
BD_C	Depth-1 m	Illite, kaolinite and quartz
BD_D	Depth-1 m	Kaolinite, illite, quartz and vermiculite

in aiding civil engineers to predict the effect of clay to the soil engineering properties are namely kaolinite, illite and montmorillonite. Though montmorillonite has the worst effect on soil load bearing capacity but kaolinite and illite which are the major clay minerals observed in the study area also have serious effect on the soil load bearing capacity especially under the condition on which they occur that is having high water saturation. The presence of these clay mineralogy (kaolinite and illite) couple with the high water saturation suggest they probably contributed significantly to the subsidence/settlement observed in this area.

Conclusions

Distinct subsurface lithologies characterizing the investigated area at Badia was delineated using the GPR and geotechnical techniques. The GPR data were able to delineate four distinct substrata layers to about 14 m depth. These materials consisted sandy clay (topsoil) which in most places are from sand fills, peat with clay intercalation, clay with peat infusion and sandy clay. Other lithologies as shown by the borehole logs beyond the 14 m depth are sand and silty sand. Highly saturated clay materials couple with massive organic material (peat) which is known to be an incompetent foundation materials occurred from the ground surface to a depth far beyond the 2 m foundation depth of the canal structure. The peat thickness and depth vary across the study area. For instance, from the borehole logs, its thickness ranges from 4.5 to 18 m, while the area covered by the GPR survey reveal peat thickness between 4.0 and 10.0 m. The peat was found to exhibit high compressibility and low consolidation coefficient. The material also exhibit high degree of water saturation, liquid limit and plastic index; characteristics alluding to incompetent subsoil material. Using the UCS system, the subsurface materials of the study area are classified into OH-Pt, OH, SC and SM. XRD analysis identified kaolinite, illite and quartz as the major component minerals in the peat soil of which the presence of kaolinite and illite coupled with their high level water saturation might have contributed significantly to the observed subsidence/settlement.

Authors' contributions

IEE carried out the acquisition and processing of the GPR data and the interpretations of the GPR and geotechnical data. AAA design the survey pattern and decide on the various methods to be applied to achieve our objectives and also did the manuscript proof reading. OA acquire and analyze the geotechnical data. All authors participated in drafting the manuscript. All authors read and approve the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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References

1. Adepelumi AA, Fayemi O (2012) Joint application of ground penetrating radar and electrical resistivity measurement for characterization of subsurface stratigraphy in southwestern Nigeria. *J Geophys Eng* 9(2):397–412. doi:[10.1088/1742-2132/9/4/397](https://doi.org/10.1088/1742-2132/9/4/397)
2. Evinemi IE (2015) Investigation of structural failure of a sinking canal using ground penetrating radar (gpr) and geotechnical techniques. Unpubl. Report, Department of geology, Obafemi Awolowo University, Ile-Ife
3. Francke J, Yelf R (2003) Applications of GPR for Surface Mining//Proc. of the 2nd International Workshop on Advanced GPR. In: Yarovoy A (ed). Published by I EEE: International Research Centre for Telecommunications and Radar, Delft University, Netherlands. p 115–119

4. Bakker M (2004) The internal structure of pleistocene push moraines—Ph.D. Thesis. In: Yelf RJ (2007) Application of Ground Penetrating Radar to Civil and Geotechnical Engineering Queen Mary College, Univ. of London. TNO Netherlands. p 177
5. Jol HM, Bristow CS (2003) GPR in sediments: advise on data collection, basic processing and interpretation, a good practice guide. In: Bristow CS, Jol HM (Eds) Ground penetrating radar in sediments. Special Publication, vol 211, Geological Society, London, pp 9–27
6. Yelf RJ (2007) Application of ground penetrating radar to civil and geotechnical engineering. *Electromagn Phenom* 7(1):102–117
7. Adegoke OS (1969) Eocene stratigraphy of southern Nigeria. *Bureau of Geology and Mining* (69):23–46.
8. Billman HG (1976) Offshore stratigraphy and paleontology of the dahomey embayment. *Proc 7th Afri Micropal Coll Ile-Ife*, p 27–42
9. Kim JH, Cho SJ, Yi MJ (2007) Removal of ringing noise in GPR data by signal processing. *Geosci J* 11(1):75–81. doi:10.1007/BF02910382
10. Adepelumi AA, Fayemi O, Akindulureni J (2013) Geophysical mapping of subsurface stratigraphy beneath a river bed using ground penetrating radar: Lagos Nigeria case study. *Univers J Geosci* 1(1):10–19
11. Davis JL, Annan AP (1989) Ground penetrating radar for high resolution mapping of soil and rock stratigraphy. *Geophys Prospect* 37:531–551
12. RajuNarasimha PSR, Pandian NS, Nagaraj TS (1995) Analysis and estimation of Coefficient of consolidation. *Geotech Test J* 18(2):252–258
13. Knight RJ, Enders AL. (2005) An introduction to rock physics principles for near surface geophysics. In: *Near Surface Geophysics Society of Exploration Geophysics*. p 31–70
14. Taylor RK, Cripps JC (1984) Mineralogical controls on volume change. In: Atewell PB, Taylor RK (eds) *Ground movements and their effects and structures*. Surrey University Press, Glasgow, pp 268–302
15. Annan AP (2005) Ground penetrating radar. In: Butler DK (ed) *Near-surface geophysics*, chap 11. Society of Exploration Geophysicists, Tulsa, Oklahoma, pp 357–438
16. Santamarina JC, Klein KA, Fam MA (2001) *Soils and waves*. John Wiley and Sons, LTD, New York, p 488
17. Reynolds JM (1997) *An introduction to applied and environmental geophysics*. John Wiley and Sons, Chichester, p 796
18. Tung LT, Huang YT (1994) GPR test on the structure of shallow stratum. *Spec Publ Cent Geol Surv* 8:137–143
19. Agagu OK (1985) A geological guide to bituminous sediments in southwestern Nigeria Department of Geology, University of Ibadan (**Unpubl. Report**)
20. Francis NH (1952) Importance of clay in applied soil mechanics. *Clays Clay Miner* 1(1):191–195

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