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Research Paper

Peat stratigraphy mapping using ground penetrating radar and geotechnical engineering implications

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Abstract

Ground Penetrating Radar (GPR) surveys was carried out in southwestern part of Lagos, Nigeria with a view of delineating the subsurface peat stratigraphy that would aid geotechnical engineering design of the appropriate soil stability processes . The GPR study was conducted along seven (7) parallel traverses trending E-W using the GSSI SIR-3000 200MHz monostatic shielded antenna. The mineralogy, micro-fabrics and morphology of the delineated stratigraphy was determined using the scanning electron microscope (SEM) and X-Ray diffraction (XRD) methods. The results obtained revealed the presence of five subsurface geological layers, distinct geomorphological features, and high, moderate and low amplitudes, to continuous and discontinuous planar radar facies structures. Borehole information confirms the occurrence of shallow peat and plastic clay layers beneath the area. SEM and XRD analyses of the field samples obtained showed the dominance of kaolinite, illite and quartz minerals in the clay/peat mapped. The derived engineering parameters suggest that the peats found in the area are fibrous peat with low strength and medium to low bedding stress. It is observed that the peat generally depict high compressibility value and low shear modulus. Our findings confirm the efficacy and relevance of GPR technique for pre-construction engineering investigations.

Keywords: *Compressibility, GPR, Mineralogy, Peat Stratigraphy, Soil Stability.*

1. Introduction

In broad terms, subsurface exploration and soil investigations are important parts of civil and/or geotechnical engineering, where most of the designs are based on the results obtained from these methods. In-situ testing are practiced to determine the properties of subsurface materials using conventional methods of boring, standard penetration tests and cone penetration tests that provide information at a particular point, but spatial variation of geotechnical material and rock depth are essential for effective design of foundation and basement floors.

In the last three decades, the involvement of geophysics in civil and environmental engineering has become a promising approach (Littlejohn, 1991; Anon, 1993). In the case of building construction, geophysics can be used to map the subsurface defects. The sources of hazards in civil engineering construction include faults, fractures and undetected near-surface structures, such as cavities and/or inhomogeneities in the foundation geomaterials (Adepelumi and Olorunfemi, 2000). Soupios (2007) showed that the acquisition of geophysical data may greatly improve the quality of buildings under construction in civil engineering. They demonstrated that engineering geophysics is able to provide solutions for determining subsurface geologic properties beneath a proposed engineering construction site.

In modern practice, GPR method is routinely used to effectively map the spatial variation of soil and rock layers with its thickness. GPR is a non-destructive method that produces a continuous cross-sectional profile or record of desired subsurface features, without drilling, probing, or digging. This work provides information on the subsurface lithology delineated using the GPR method, the thicknesses of the lithology and the engineering characteristics estimated using empirical relations. The objectives of the project include the following: (a) to map the subsurface lithology, (b) determine thickness and depth of the subsurface lithology, (c) determine the integrity and/or geotechnical engineering properties and the bedding stress of the subsurface lithology delineated, (d) identify the most appropriate technology for pre-injection stabilizing the subsurface lithology.

2. Geological setting

The study area is in the southern fringe of metropolitan Lagos in Nigeria. It is one of the six communities in Apapa Local Government Area of Lagos State. Geographically, it is bounded by latitude 715000 N and 716000 N, and longitude 538600 E and 540300 E (Fig. 1).

The site is part of the Dahomey Basin of SW Nigeria. Sedimentation in this basin dates back to early cretaceous after the separation of African – South America landmasses and subsequent opening of the Atlantic Ocean (Omatsola and Adegoke, 1981). The local geology of the study area is consistent with the regional geological setting of Lagos area as described by Longe, et al., (1987). It is made up of the Benin formation (Miocene to Recent) and the recent littoral alluvial deposits (Jones and Hockey, 1964). The area lies within the Coastal Plateau geomorphic unit (Adegoke et al 1980). The area is low lying with elevation range from 0.5m to about 3.0m above mean sea-level. The area lies within the rain

forest zone of Nigeria with mean annual rainfall of above 1500 mm.
The investigated area contains good aquifers that are harnessed through hand-dug wells with very shallow depth extent. The groundwater level varies between 1 m and 2m. The water-bearing aquifers consist of sands, gravels or a mixture of the two. Textural variations from fine through medium to coarse sands and gravels occur and they are poorly to well sorted. When near the surface, the sand deposits are generally loose but become moderately dense with depth and occasionally with clay interbeds (Longe et al, 1987).

3. Methodology

For this study, ASTM D6432-11 (2011) Standard Guide for Using the Surface Ground Penetrating Radar Method for subsurface investigation was adopted. The GPR data were acquired along seven (7) parallel traverses approximately E-W, using the GSSI SIR-3000 equipment. The survey was done using a 200MHz 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 thirty-three (33) scans per meter were taken (representing 3 cm station spacing) with a sampling window of 400ns 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. GPR data were acquired both on land and water. The SIR-system and antenna were pulled manually on land during data collection while they were mounted on a wooden boat during data collection on water. All traverses were 530 m long and ran from land (marshy) to water, with traverse-traverse separation of 2.5 m (Fig. 1).
Two kinds of processing; basic and advanced processing were applied to the acquired GPR data. The basic processing structure include; data editing (which involves data reorganization, data file merging, data header background information updates, inclusion of topography information in every file), zero-offset correction, dewowing, band-pass filtering (with a centre frequency of 200 MHz and cutoff frequencies of 100 MHz and 300 MHz), filtering in wavenumber domain and application of gain functions. Two gain functions were applied to the data; Automatic gain functions and Custom gains. Automatic gains (AGC) increased the amplitude of the signal by a factor inversely proportional to the signal strength. AGC is more effective for recognizing low amplitude reflections (Neal, 2004). The custom gain provided a constant amplitude increase for the signals irrespective of the signal strength loss.
Advanced processing steps that were applied to the radar images include; Predictive deconvolution, velocity spectrum analysis and attribute analysis (Adepelumi et al, 2013, Adepelumi and Fayemi. 2012, Kim et al. 2007). The intended effect of the deconvolution process was to remove the ringing multiples associated with water layers. The attribute analyses were generated by Hilbert transformation functions, which include instantaneous frequency, instantaneous phase and instantaneous amplitude. A velocity value of 0.13 m ns^{-1} was obtained from the velocity spectrum analysis of the GPR sections and it was used for the time-depth conversion of the data.
Six soil samples were collected from the field and were analyzed in the laboratory for clay mineralogy using scanning electron microscope and x-ray diffraction methods.

4. Results and discussions

The depth of penetration of the radar signals range from 22 m to 24 m in the studied area. The results obtained from the processed GPR data are interpreted stratigraphically in terms of the radar facies, in correlation with a borehole log obtained in the area and with empirical equations to infer the in-situ engineering characteristics of the peat stratigraphy delineated from this study.

4.1. Radar facies

The radar facies observed defines the vertical profile as well as the architectural element - scale features described and interpreted in the borehole log. The facies are defined using the basic principle of seismic interpretation techniques on the basis of reflection amplitude, continuity and configuration (Mitchum et al., 1977). Five radar facies were recognized from the GPR sections (Table 1).
High amplitude planar reflections (F1):
It is characterized by high amplitude, planar/even, parallel to sub parallel, horizontal reflection with good continuity. It is interpreted as the top soil/sand-filled area.
Moderate amplitude discontinuous reflections (F2):
It is characterized by moderate amplitude, parallel sinuous/wavy reflections. It is interpreted as silty-clay.
Low amplitude continuous reflections (F3):
It is the most prominent feature/unit of interest in the study area. It is characterized by low amplitude, parallel sinuous/wavy reflections, often mottled up in places. It is interpreted as peat.
Moderate amplitude reflections (F4, F5):
It is characterized by sub-parallel sinuous (at the upper portion) and wavy (toward the bottom of the radar) reflections, moderately amplitude reflections. This radar facies is interpreted as layer of sandy clay (F4) and silty-sand (F5).

Table 1: Description of Radar Facies Obtained From the GPR Sections

FACIES	LITHOLOGY	RADAR CHARACTERISTICS
F1	Top soil/sand-filled layer	High amplitude planar reflections
F2	Silty clay	Moderate amplitude discontinuous reflections
F3	Peat (with intercalations of clay)	Low amplitude continuous reflections
F4	Sandy clay	Moderate amplitude reflections
F5	Silty sand	Moderate to high amplitude reflections

The GPR stratigraphy obtained on Traverse 1 (Fig. 2) reveals relatively thin parallel to sub-parallel, horizontal reflections with good continuity which is interpreted as top soil/sand-filled layer (F1); the study area is marshy and so various portions have been sand-filled to enable accessibility. The water table exists just beneath this layer. The topsoil is absent on the portion of the traverse run on water and is replaced by the refuse- and litter-ridden water column. The topsoil is underlain by a layer with high amplitude, sinuous, horizontal, chaotic, moderately continuous reflections. This layer of silty-sand (F2) has thickness varying from 0.8 to 4.5 m. Low amplitude (almost reflection-free) planar, moderately continuous reflections (F3) with a thickness of 3.5 to 7 m underlay the silty-sand unit. This is the layer of interest (peat) and the depth of occurrence ranges from 1.5 m to 9 m along the traverse. Moderate to high amplitude, planar, horizontal, sub-parallel reflections underlay the peat layer. This sandy/clayey layer (F4) had a marked boundary with the overlying peat, although the radar image showed a gradual transition between these sandy/clayey layers. A thick sequence of discontinuous chaotic reflections with high amplitude and sinuous configuration interpreted as silty-sand (F5) underlie the sandy/clayey unit.
The GPR stratigraphy obtained on traverse 2 (Fig. 3) showed similarity to traverse 1. The geometry of the river bed was clearly shown on the GPR section and the river base had a maximum depth of 3.5 m. Domestic waste such as refuse, sewage and plants were seen on the river and such materials were held in suspension in the water. Furthermore, part of these had settled to the base as undecomposed peat/clay and waste with thickness range of 1 to 2m. This layer directly overlay the peat which has similar geometry with that seen along traverse 1. The clayey-sand layer beneath the peat unit had straddled in it, sandy clay units in places, showing a gradual change in thickness and geometry of the clayey/sandy layer from land to water.

The GPR stratigraphy obtained beneath traverse 2 showed similarities to traverse 3, but for the presence of sedimentary structures (ripples marks) within the peat (Fig. 4), which are indicators of the transportation medium and paleo-current direction of the peat. As indicated by the ripple marks, the peat was possibly deposited in fluvial environment with the N-S direction of flow.

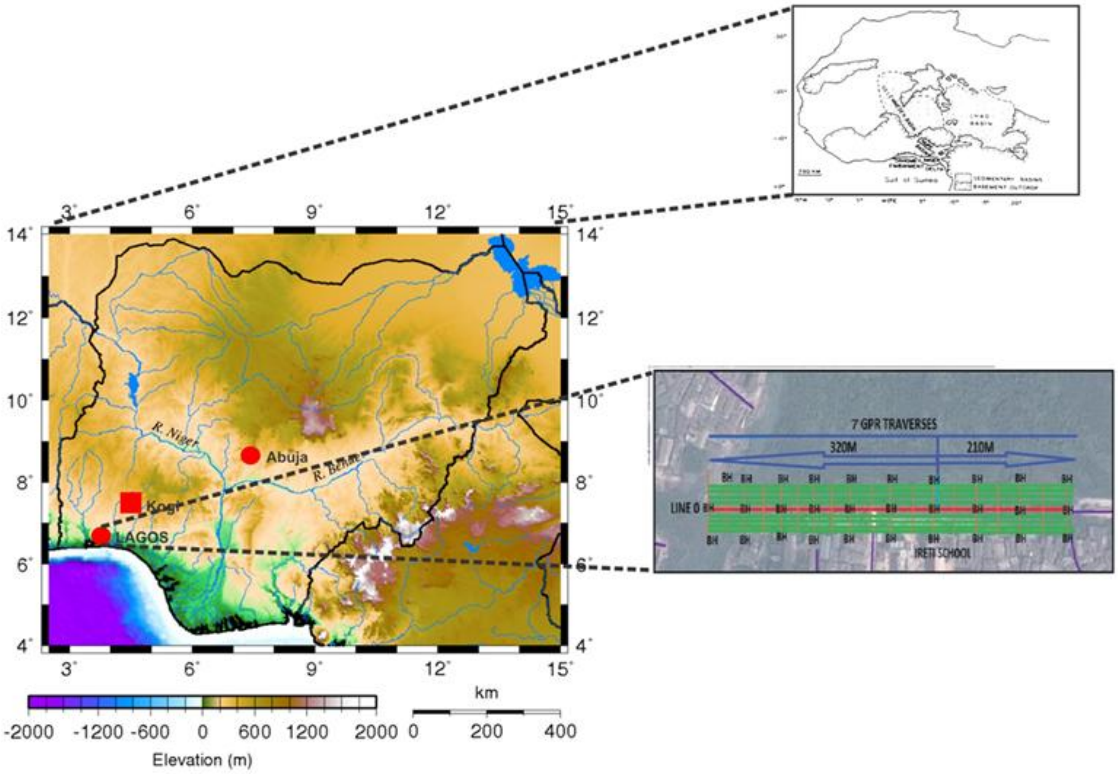


Fig. 1: Location Map of the Study Area Showing the GPR Traverses and Borehole Locations Insert.

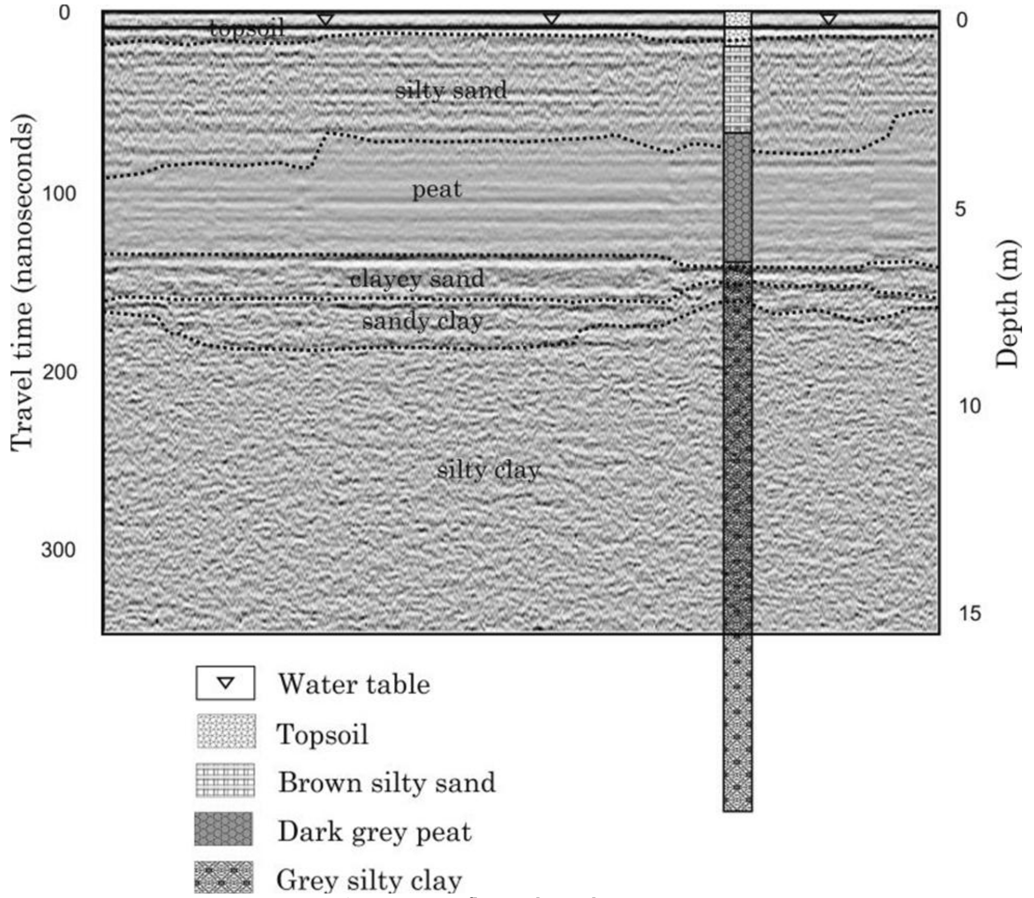


Fig. 2: GPR Reflection beneath Traverse 1

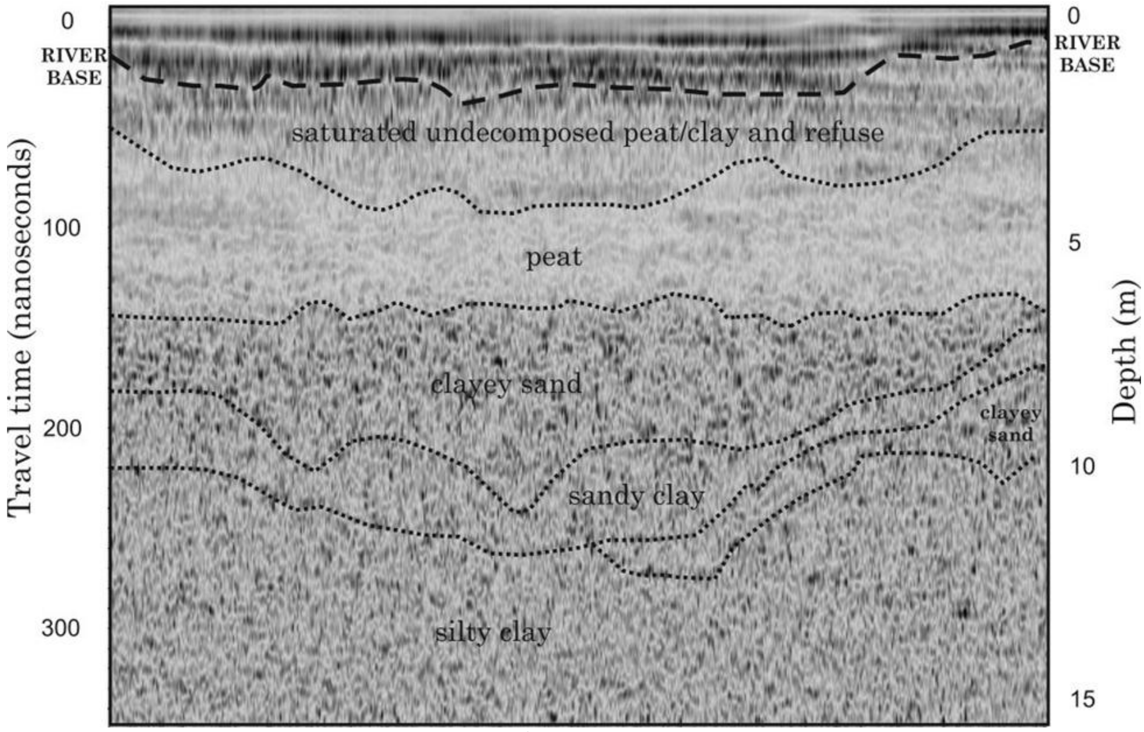


Fig. 3: GPR Reflection beneath Traverse 2.

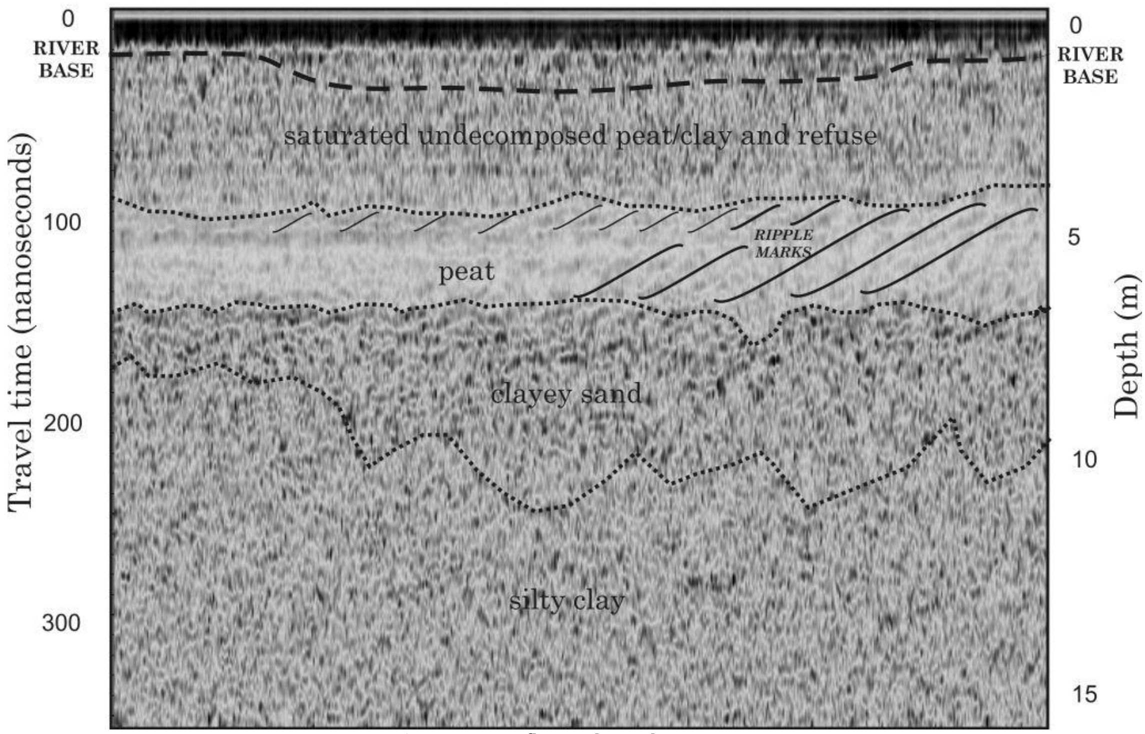


Fig. 4: GPR Reflection beneath Traverse 3

Fig. 5 to 8 shows the geological sections obtained for traverse 4 to 7 respectively. Five distinct lithologic sequences comprising of: topsoil, peat with clay intercalation, sandy clay, pebble and/or rubble, and silty sand are seen to characterize the subsurface of the area investigated. The lateral and vertical inhomogeneities of the subsurface lithology are well depicted. Also, the depth extent and the thickness of the peaty soil are appropriately delineated, thus assisting the process of estimating the volume of the chemical that will be injected into the peat for proper ground injection and soil stabilization if the option of chemical injection is adopted for the ground improvement.

In Fig. 9, a contour map of the peat thicknesses is shown; while Fig. 10 illustrates a geologic section drawn across the seven surveyed traverses. These two figures aid the proper deciphering of the peat thickness morphology and geometry that exist beneath the investigated site. Also, an obvious decrease in depth to the Peaty soil from Traverse 1 to 7 is evident.

4.2. SEM and XRD

Laboratory analyses using scanning electron microscope (SEM) and XRD were carried out on field samples obtained from the investigated site. The samples are made up predominantly of quartz, illite and kaolinite minerals. The results of the SEM are summarized in Table 2. Fig. 12-15 show the intensity (cps) plots of the samples

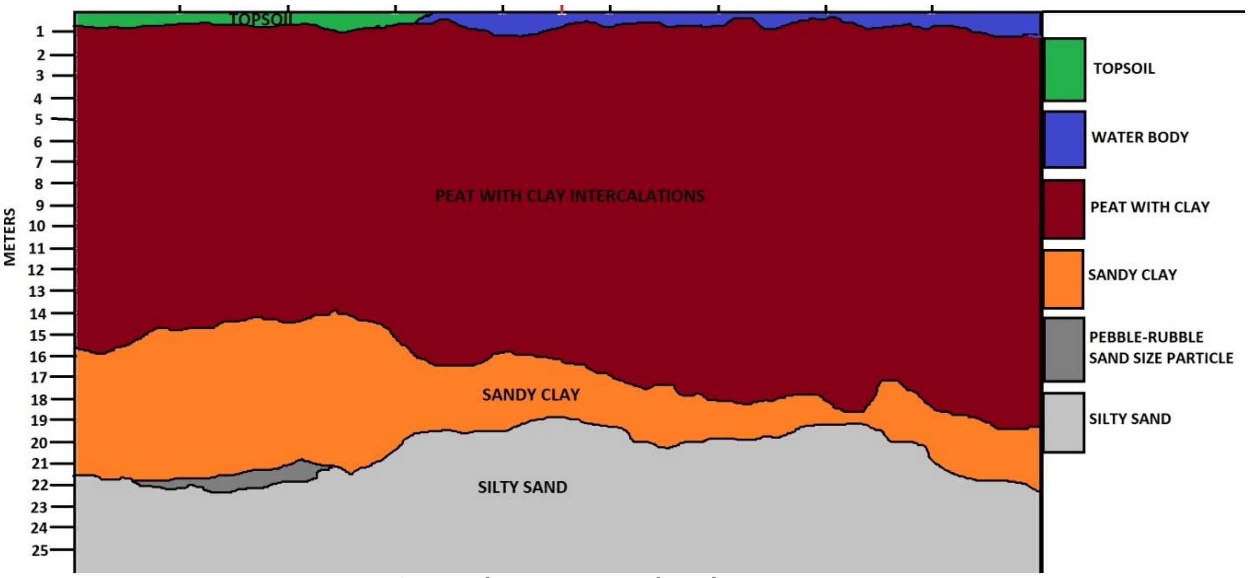


Fig. 5: Geologic Cross Section beneath Traverse Four

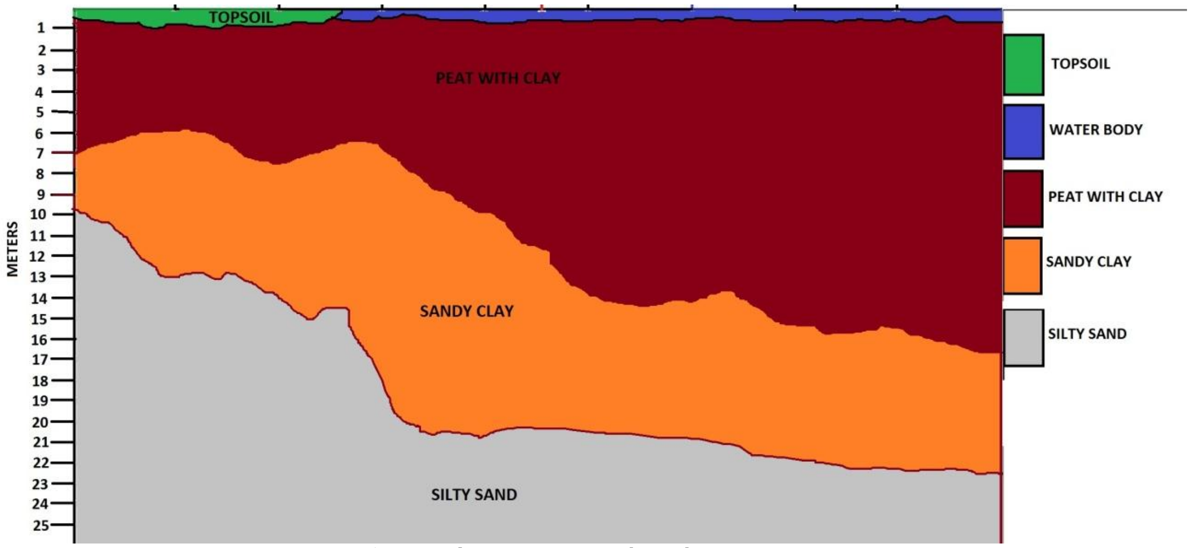


Fig. 6: Geologic Cross Section beneath Traverse Five

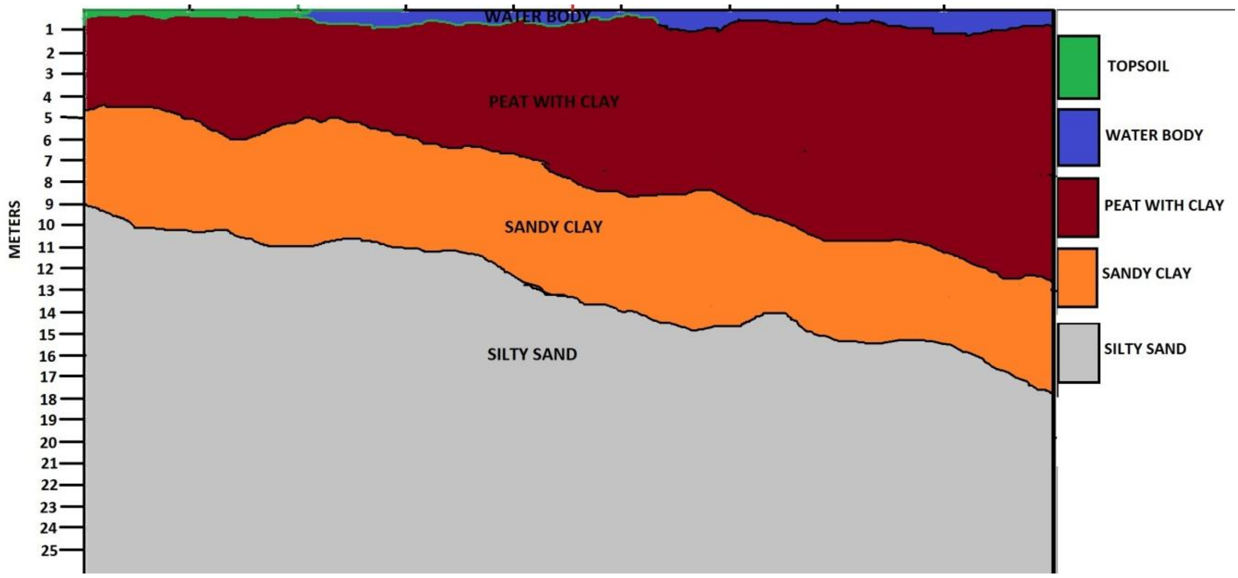


Fig. 7: Geologic Cross Section beneath Traverse Six

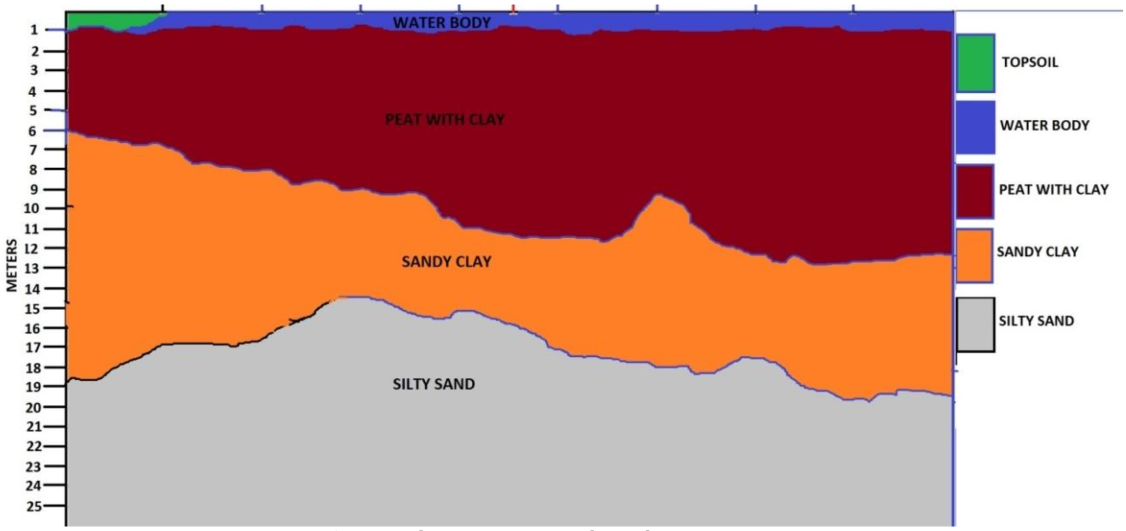


Fig. 8: Geologic Cross Section beneath Traverse Seven

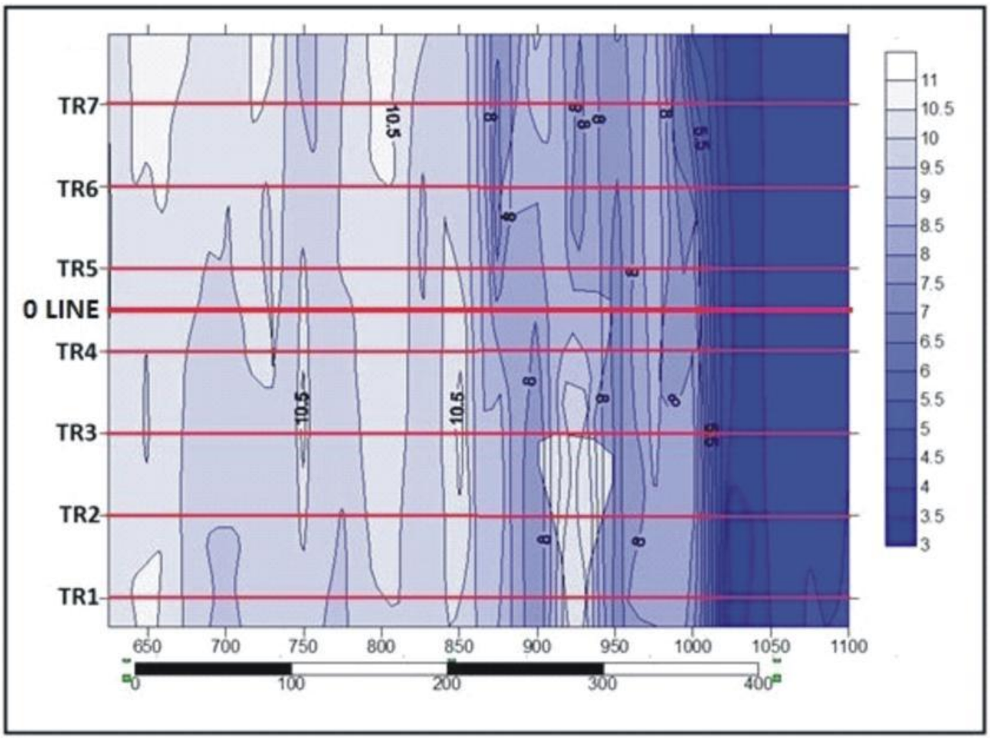


Fig. 9: The Contoured Map of the Peat Thicknesses (Metres) Using the Seven Traverses.

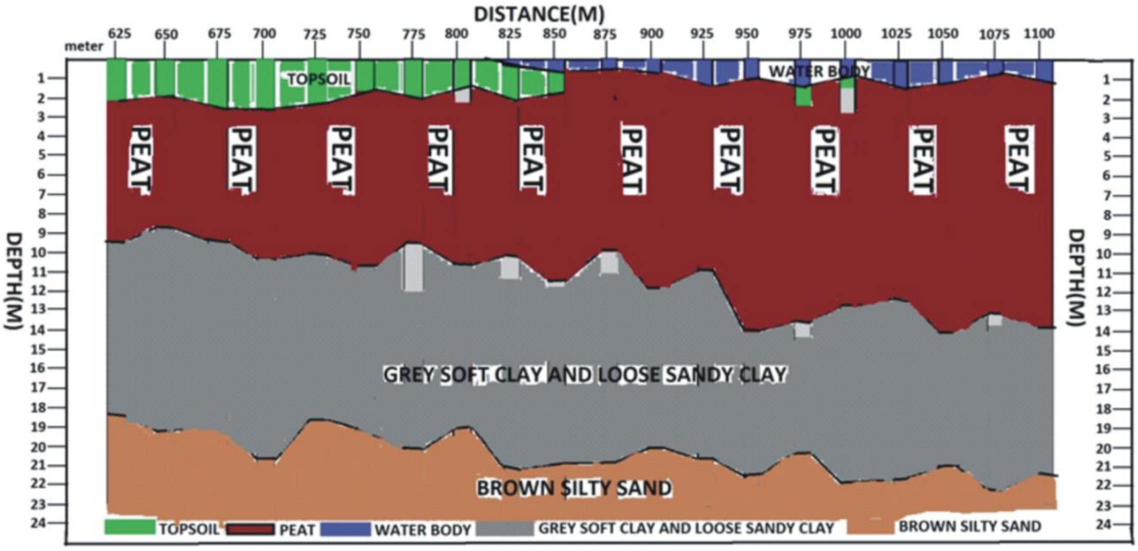
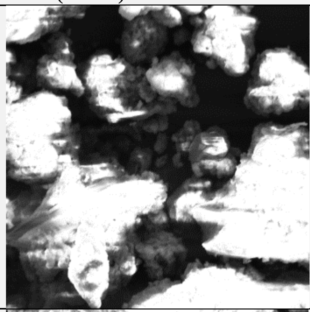
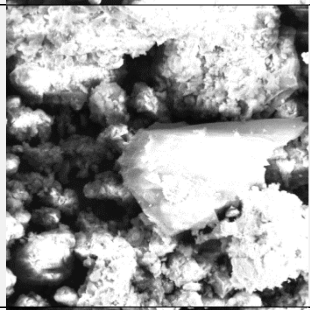
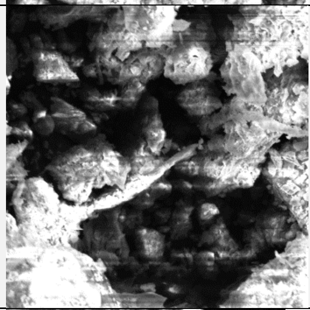
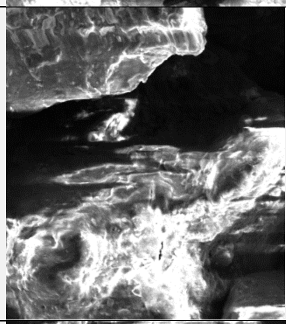
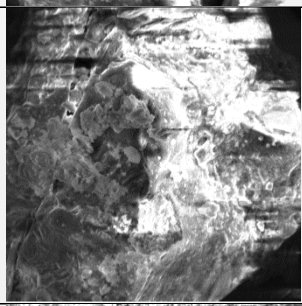
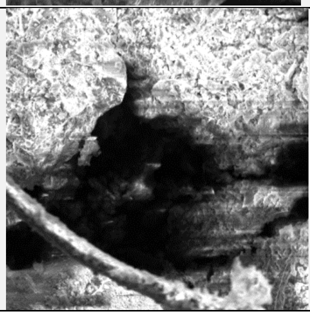


Fig. 10: Subsurface Cross Section across the Study Area Showing the Peat Stratigraphy

Table 2: SEM and XRD Results

Sample	Analysis	SEM (×1000)
BD_A	Detrital quartz grains coated with filamentous pore-lining and pore-bridging authigenic illite and kaolinite verm on the detrital quartz grain. Open and interconnected pores lined with authigenic ribbons form a mat, coating detrital grain surfaces and also bridging the pores between grains creating permeability barriers to fluid flow. Kaolinite books are arranged face-to-face into an elongated stack called a "verm." XRD analysis yields these major clay minerals showing the dominant of illite, quartz and kaolinite respectively.	
BD_B	Detrital quartz grain with well crystallized, authigenic kaolinite partly filling pores. The kaolinite occurs as stacks of books. Individual crystal is distinct and filamentous illite occurs on their surfaces. The XRD analysis result confirms the high presence of kaolinite, then illite and quartz.	
BD_C	Authigenic illite rimming area of grain contact on a detrital quartz grain. The perimeter of the grain contact area shows individual illite ribbons. Well crystallized authigenic kaolinite partly fills pores between detrital quartz. Precise identification is actually based on XRD analysis showing illite, kaolinite and quartz.	
BD_D	Blocky, authigenic pore-filling kaolinite. The kaolinite occurs as pore-filling preventing the growth of authigenic quartz grain. Ribbon form illite lined the detrital quartz contact surfaces. XRD analysis shows high concentration of kaolinite and quartz with little illite mineral and a stain of feldspar.	
BD_E	Kaolinite on a detrital quartz grain. The presence of kaolinite is confirmed by the high kaolinite intensity obtained in the XRD analysis. Sheets of filamentous illite occur on the surface of the kaolinite.	
BD_F	Massive detrital illite composed of irregular, flake-like clay platelets. The flaky morphology of this detrital illite is not unique to illite, thus is of no help in identifying this clay. Precise identification is therefore based on X-ray diffraction (XRD) analysis. The illite coats the detrital grain quartz, impregnated with kaolinite pore-filling.	

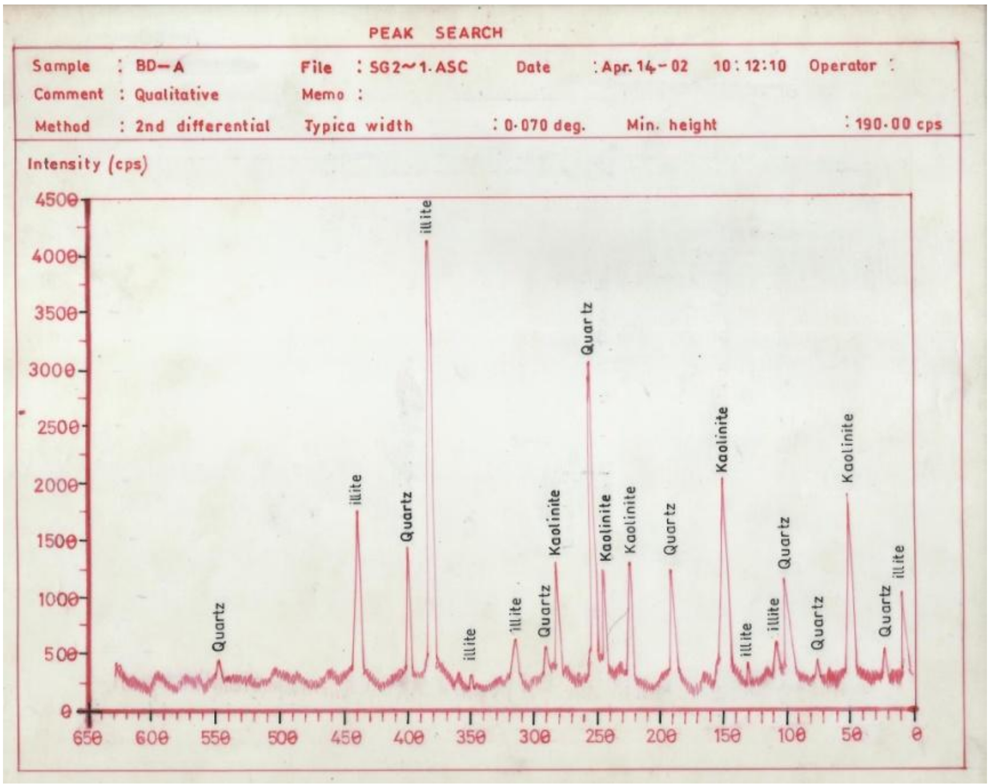


Fig. 12: Intensity Plot of Sample BD_A

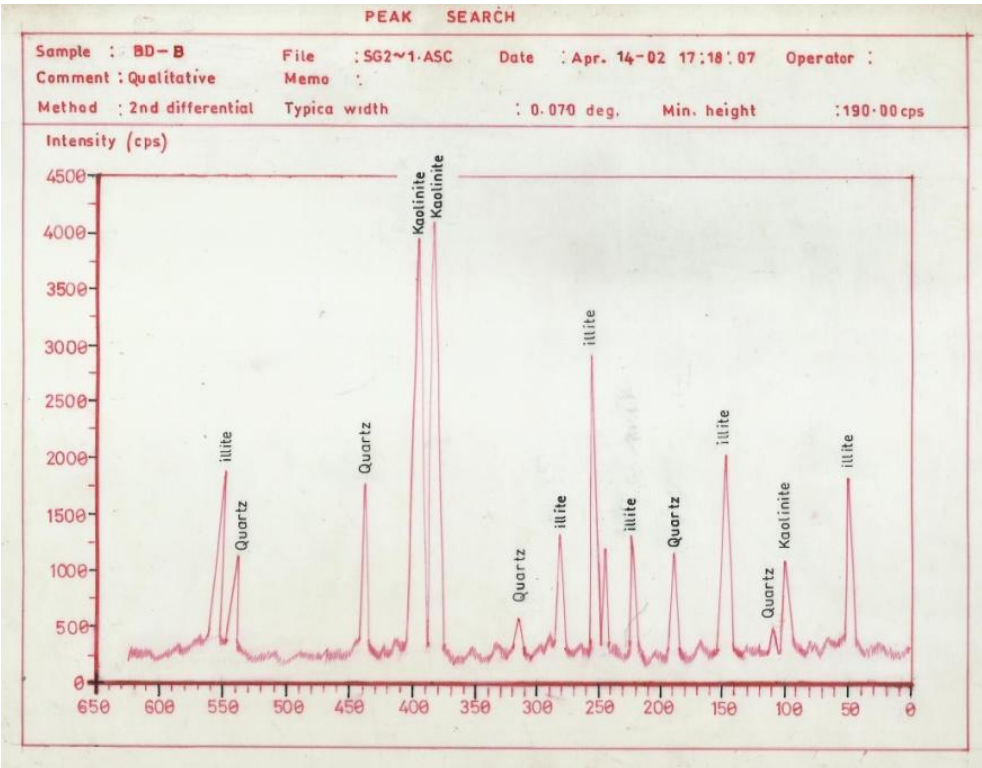


Fig. 13: Intensity Plot of Sample BD_B

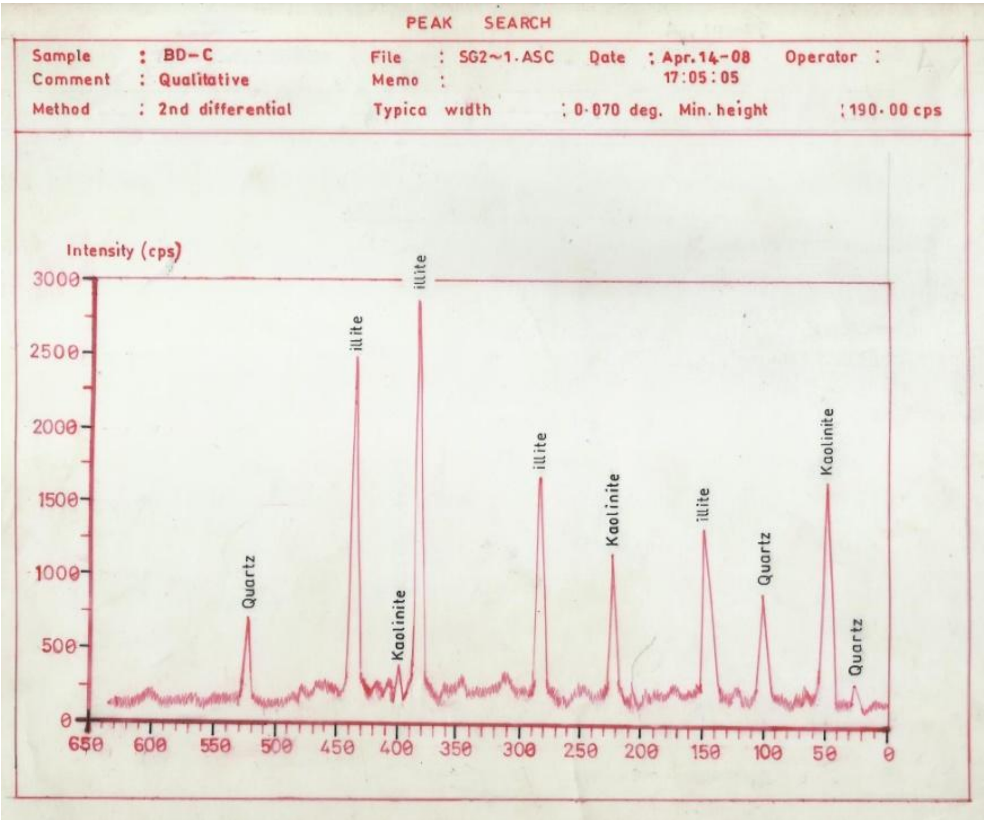


Fig. 14: Intensity Plot of Sample BD_C

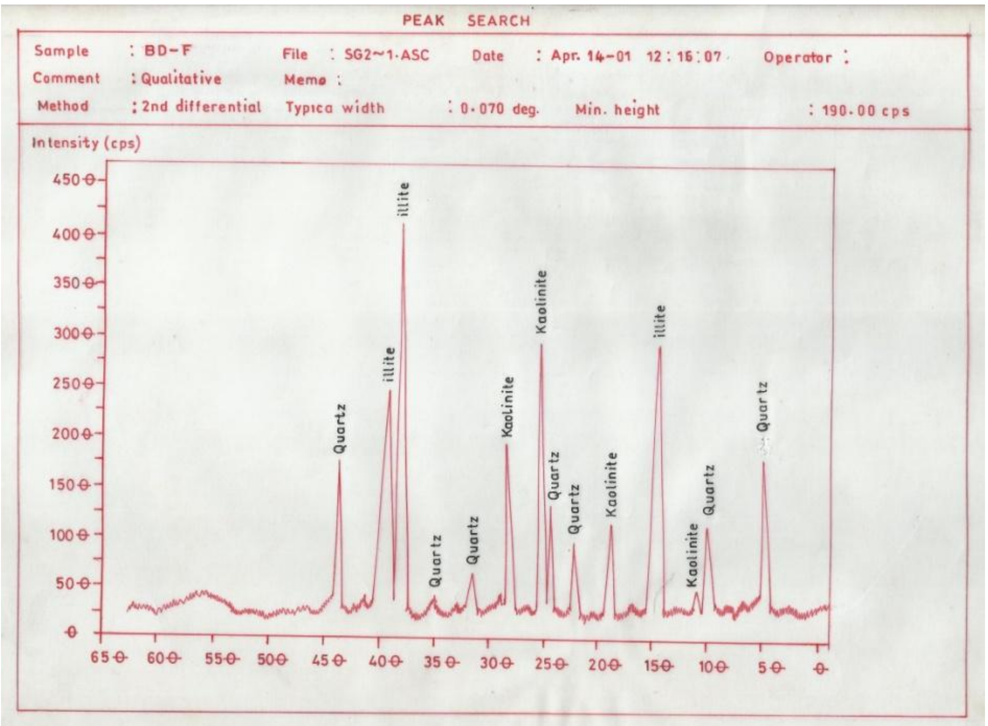


Fig. 15: Intensity Plot of Sample BD_F

4.3. Engineering parameters derived for the peat

An attempt was made to calculate the intrinsic engineering properties of the peat unit from the geometry and thickness of the peat layer(s) observed on the GPR sections with the use of empirical equations. The empirical equations given by Chang et al. (2006), Lal (1999), Topp (1980), Olhoeft (1979a) were employed to derive the engineering parameters such as the bedding stress (deviatoric stress), porosity, density, Poisson ratio, elastic moduli etc. of the peat unit. The values of the engineering parameters obtained are shown in Table 3.

Peat soil are generally defined as unconsolidated organic material consisting largely of organic residues accumulated as result of incomplete decomposition of dead plant constituents under conditions of excessive moisture (Landva, 2007). It is generally accepted that the organic matter present in peat soils causes a detriment to their geotechnical and engineering qualities (Malkawi et al. 1999). Engineers worldwide consider peat soils as problematic soil because of their perceived abnormal geotechnical properties.

These soils, according to Kazemian et al. (2011) are geotechnically problematic and cause instability problems such as development of slip failure, local sinking, and massive primary and long term settlement even when load increases moderately, because of their low shear strength and high compressibility. Therefore Peaty soils are considered not suitable as foundation soils as they are weak and highly compressible (Duraisamy et al. 2007).

As shown in Table 3, for the depth range where the peat samples were obtained, the porosity of the peat varies between 31 and 35%. The engineering properties such as velocity, Young modulus, shear modulus and bulk modulus of the samples were within the range as reported by Huat (2004) and Duraisamy et al. (2007) for peat found in the tropical region.

It is evident from the result obtained in this study using the empirical relations that the peat investigated falls in the category of fibrous peat having high compressibility value, low internal frictional angle and medium to low bedding stress. They also exhibit low elastic properties such as low shear modulus, low bulk modulus and low Young modulus values (Table 3). The values derived strengthen the needs to apply soil stabilization techniques in the area. The density values obtained are uniquely uniform with varying depth of 1.5 to 18 m. The density values ranges from 2.02 to 2.04 g/cc.

Chang et al. (2006) showed that along with the unconfined compressive strength (UCS) of rock and soils, the angle of internal friction is another strength parameter necessary to estimate rock strength at depth. The angle of internal friction is a measure of the dependence of rock strength on confining pressure such that a higher value of Φ indicates a higher sensitivity of strength to confining pressure. They further showed that there is rarely a unique value of friction angle for a rock, because the strength points as a function of confining pressure are not usually linear. Friction angle depends on the confining stress range over which the data are fit.

From this study, the predicted internal friction angle increases monotonically from 3° to 10° as P-wave velocity increases from 1.83 km/s to 1.87 km/s, and as the as S-wave velocity increases from 0.883 km/s to 0.89 km/s. The derived internal friction angle indicates that the peat investigated is possibly heterogeneous in nature. However, we cannot rule out the possibility that the empirical equation used probably underestimates the internal friction angle for the peat.

The unconfined compressive strength (UCS) of the peat estimated using the empirical relations are considered to be generally very low to low. The peat possesses UCS values that range from 6.2 to 12.3 MPa.

The derived engineering parameters for this study suggest that the Peat found in the investigated area are fibrous peat with low shear strength, medium to low bedding stress and high water volume content. The engineering implications of these derived values imply that for any engineering structure(s) to be constructed at any of this location, proper and adequate soil stabilization and improvement processes such as chemical injection (wet mixing), deep mixing (Cortellazzo and Cola, 1999; Hebib and Farrell, 1999), and in-situ stabilization must be embarked upon in order to strengthen the sedimentary soil. If the construction exercise is carried out without applying any of the suggested ground improvement techniques, the likelihood of the soil undergoing differential settlement and ground subsidence is very high in the area.

Table 3: Engineering and Elastic Parameters of the Peat Derived Using Empirical Relations

DEPTH (m)	POROSI-TY (Ø)	Vp (km/s)	Vs (km/s)	Density (g/cc)	Poisson ratio (μ)	Young modulus (GPa)	Shear modulus (GPa)	UCS (MPa)	Internal friction (θ)	Bulk Modulus	Bedding Stress (dP)
1.5	0.33	1.83	0.88	2.02	0.35	4245.3523	1575.0289	7.1935	4.01	4646.01	4.88
2	0.32	1.82	0.88	2.02	0.35	4208.2304	1261.2644	6.2953	4.01	4605.18	4.27
3	0.35	1.84	0.89	2.03	0.35	4312.1256	1299.7876	9.3928	3.02	4719.45	6.37
4	0.34	1.83	0.88	2.02	0.35	4245.3523	1375.0289	7.1935	3.73	4646.01	4.88
5	0.35	1.85	0.89	2.03	0.35	4369.9804	1321.2395	12.264	3.91	4783.09	8.31
6	0.33	1.84	0.89	2.03	0.35	4342.0939	1210.8995	10.733	5.03	4752.41	7.28
7	0.33	1.83	0.89	2.02	0.35	4279.9298	1387.8498	8.2199	5.00	4684.04	5.57
8	0.32	1.84	0.89	2.03	0.35	4312.1256	1399.7876	9.3928	5.01	4719.45	6.37
9	0.34	1.86	0.89	2.03	0.36	4208.2304	1293.7719	7.1935	6.32	4646.01	4.27
10	0.35	1.87	0.88	2.02	0.36	4312.1256	1375.0289	10.264	6.30	4783.09	6.37
11	0.35	1.86	0.88	2.03	0.34	4245.3523	1321.2395	8.6314	6.01	4752.41	6.88
12	0.34	1.84	0.88	2.03	0.34	4369.9804	1204.8005	8.1099	3.05	4684.04	8.31
13	0.35	1.85	0.89	2.02	0.35	4208.2304	1212.8498	7.3785	8.02	4719.45	6.28
14	0.34	1.87	0.88	2.03	0.35	43654.910	1610.8995	7.1935	4.35	4646.01	6.57
15	0.35	1.88	0.89	2.04	0.35	4342.0939	1587.8498	11.204	4.38	4783.09	6.37
16	0.32	1.84	0.89	2.04	0.35	4271.9168	1578.7171	8.7001	10.01	4746.01	7.27
17	0.31	1.88	0.89	2.04	0.35	4356.1206	1594.6090	9.2009	10.00	4605.18	8.31
18	0.31	1.87	0.88	2.04	0.35	4371.9812	1618.8789	9.2201	10.01	4719.45	8.28

5. Conclusion

Of all the soils suitable for foundation support, the presence of organic materials make peat and organic soils in general, difficult foundation materials because they exhibit very high compressibility compared with inorganic soils such as sands and gravels. The behaviour of a soil mass under load depends upon many factors such as the properties of the various constituents present in the mass, the degree of intensity, the degree of saturation, the environmental conditions etc. The inapposite property of peats to engineering works has led to various invasive investigations to determine their compressibility and engineering properties in order to evaluate foundation settlements. High resolution Ground Penetrating Radar (GPR) survey has revealed the general geometry and architecture, sedimentary units and patterns existing in the investigated site in Lagos Nigeria. The GPR data acquired in the study area revealed the presence of five distinct radar facies (F1-F5) namely; topsoil, silty clay, peat, sandy clay and silty sand. The stratigraphic unit of interest, peat, was correlated across the seven GPR traverses studied and revealed the peat layer has varying thickness from 3 m to 13 m in the subsurface. The depth of occurrence of the peat also ranged from 1.5 m to 14 m. An obvious decrease in depth to the peat vis-à-vis peat thicknesses exist between traverses 1 to 7 was obtained. Correlation of the results of the GPR data with the borehole log suite obtained showed marked similarities in depth and thickness of the peat bogs. Furthermore, an attempt was made to infer the in-situ engineering and elastic properties of the peat. The derived engineering parameters show that the Peat found in the investigated area are fibrous peat with low strength, medium to low bedding stress and high volumetric water content (VWC). Laboratory analyses of field samples indicated the presence of kaolinite, illite and quartz minerals in the clay/peat mapped in the area.

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