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Geotechnical Properties of Soils in a Crude Oil Impacted Site in the Niger Delta, Nigeria.

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Abstract: *- The geotechnical properties of soils at a 44-year old hydrocarbon spill site were determined and the changes in soil properties due to the spill were evaluated. The aim was to assess the magnitude and intensity of hydrocarbon contamination and consequent modification of the geotechnical properties of the impacted soils. The study employed 2-D electrical imaging to assess the spatial extent of subsurface contamination, followed by sampling and laboratory testing of soils obtained from 5m deep auger borings. The soil is clayey sand consisting of 18 – 35% fines and 55 – 82% sand. 2-D electrical imaging gave very low resistivities (38 - 220Ωm) at about 7m which is within the depth of the first aquifer in the region, indicating possible contamination of the shallow water bearing soils. Total Petroleum Hydrocarbon (TPH) concentrations of the soils decreased from approximately 5000ppm at 1m to 2000ppm at 5m compared to background values of 50 ppm in the Niger Delta. There were significant changes in liquid limit (35- 42%) and plastic limit (17- 24%) when compared with the uncontaminated soils with values of 39 - 47% and 21 - 26% respectively. Undrained cohesion ranges of 20-31 kPa were obtained for the polluted soils compared to 43 kPa for the uncontaminated soils. Overall results showed similar trends in changes in properties implying that the higher the oil in the soil, the worse are the engineering properties of the soils. Comparisons of the geotechnical properties of the polluted and unpolluted soils yielded pollution indices (PI) which indicate three levels of changes: potentially significant changes (PI<0.5) in soil plasticity, significant changes (0.5≥PI≤1.0) in shear strength parameters and very significant changes (PI>1.0) in consolidation coefficients. These results imply that the hydrocarbon has generally modified the engineering properties of the soils, with the most significant reduction observed in the shear strength parameters and consolidation coefficients.*
Keywords*: crude oil, geotechnical, hydrocarbon, Niger Delta, polluted, soils, TPH*

I Introduction

The Niger Delta area which provides the bulk of current oil produced in Nigeria is crisscrossed by a large network of pipelines that transport crude from production platforms to processing or gathering plants. Very often, oil spills occur more by human vandalisation of the pipelines than by other known causes including equipment failure, corrosion of delivery pipelines and accidental leakages. In the present study, the site was affected by an oil spill in 1970. [1] undertook a study of soil samples recovered from test holes augered at the site and found that soils were smeared with crude oil from the surface to a depth of 4m. No literature has described the changes associated with engineering properties of the underlying soils at the location due to the impact of the spill. However, it has been reported by [2] that oil contamination adversely affects soil properties and groundwater resources thus the foundation of buildings, road pavements and other earth retaining structures are likely to suffer from the modification of the geotechnical properties of the soils due changes in the soil structure. Soils are particulate earth materials made up of solid, liquid and air in three phase inter- relationship, but when impacted by crude oil or its derivatives, a fourth phase is introduced which changes the structure and properties of the soils. Before pollution by crude oil, the initial soil grain is usually surrounded by a thin film of water which holds on to the adjacent grain by a weak Van der Waal's forces. However, after being impacted by crude oil, the oil film surrounds both the original water film and the soils grains ([3], [4]. Hydrocarbon contamination alters the physical properties of soils and leads to geotechnical problems related to construction of foundation of structures on oil-contaminated soils. Results of studies on the geotechnical behaviour of oil contaminated soils [5], [6], [7], [8], [9], 10], [11], 12], [13], [14] and [15] demonstrated that oil spill significantly affects the engineering properties of soils by worsening most of the soils index and shear strength properties. There is paucity of knowledge on the extent of this phenomenon in soils in the Niger Delta area which experiences one of the highest rates of oil spillages in the world, and where the study area is located. The purpose of this study is to determine the geotechnical properties of sub soils underlying the oil contaminated study area and compare them to soils of nearby unpolluted areas. This will be used to determine the modifications of the soil properties by crude oil and to derive the associated pollution indices. The data will be useful in the safe design and construction of civil engineering structures on the soils.

II. Site Location and Description

The study area is a crude oil spill site in Ejamah-Ebubu community (Fig.1) which lies about 15km southeast of Port Harcourt located in the Niger Delta area of southern Nigeria. The site is traversed by pipelines which transport gas and crude oil across the many production platforms in the delta. The area is topographically flat with a gentle undulation whose gradient slopes gently from the southern portion towards the central part of the spill site where the flood basin is located. The oil pipeline that resulted in the spill trends northwest to southeast of the study area. A seasonal stream runs through the south-eastern flank of the spill site into the flood basin located in the central portion of the site. The land is commonly used for farming crops like cassava and plantain. Two rainfall seasons are remarkable: the wet months of March to October and relatively dry months of November to February. The average annual rainfall is 2500 mm with monthly maxima in July and October. A mean annual temperature of 33 ^{o}C is usual with high relative humidity of over 75%. The low lying areas are commonly flooded with water giving rise to swamps while higher grounds are relatively dry unless at the peak of the rainy season. Using the [16] geomorphological classification of soils in the Niger Delta region, the area falls in the clayey/sandy subsoil zone referred to as the dry flatlands and plains or upper deltaic plains which occur in the northernmost parts of the Niger Delta and consist mainly of firm, brownish sandy clays, silty clays and/or heavy clay of low to high plasticity overlying the sandy substratum. In most areas of the upper deltaic plains, the depth to water table is between 5 and 17m, but it is often less than 1m in river valleys or marshes during the rainy season. In the study area groundwater was encountered 5m below ground surface during the rainy season.

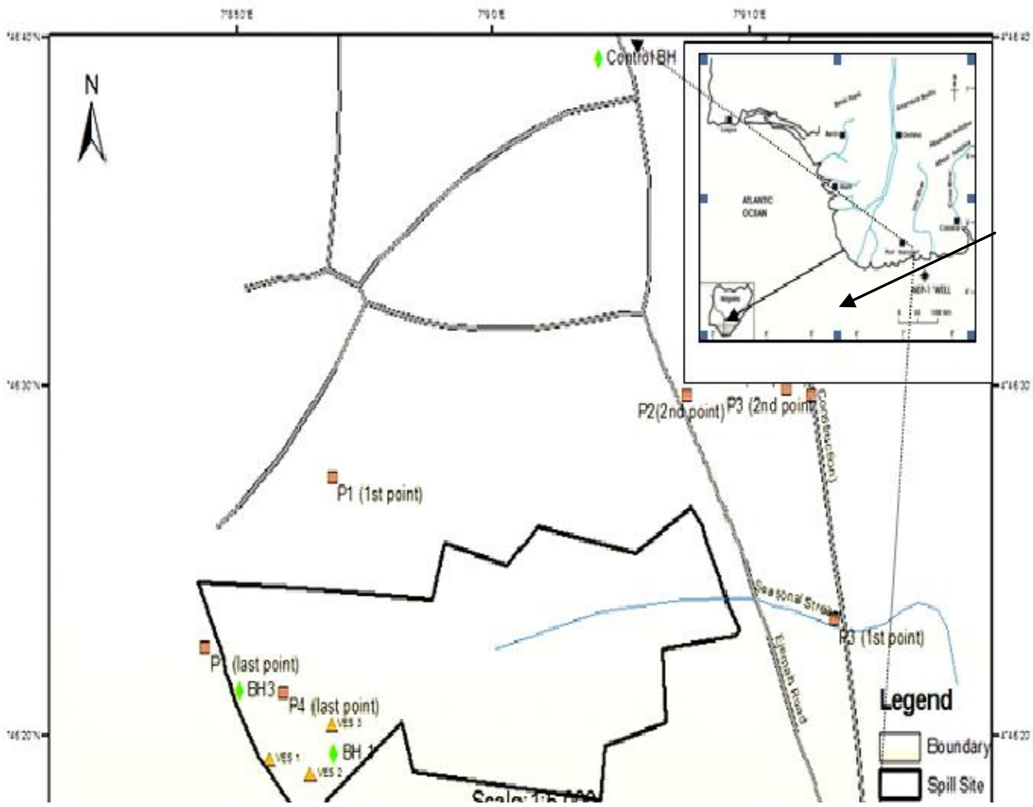


Figure 1 Map outlining the oil spill site

III. Regional Geology and Hydrogeological Setting

The geology of the Niger Delta has been extensively described by several authors and the most referenced work is that of [17]. The site is underlain by the Benin Formation which is predominantly coarse grained sandy soils with a few shale intercalations. The unconsolidated, highly porous sands of the Benin Formation have been identified as a fresh water bearing sand [18]. All aquifers in the delta region are located within this lithostratigraphic unit. Generally, in the Niger Delta, the regional groundwater occurs in four major aquifers delineated from lithologic and geophysical log within a depth bracket of 0-300 meters [19]. The first aquifer occurs between 0-45m under phreatic conditions and is the most extensively exploited, the second (50-130m) and third (136-212m) are semi- confined, while the fourth (219-300m) is perfectly confined and is the thickest. The aquifers are predominantly very fine to coarse grained sand beds with minor clays and conglomerate intercalations. In the present study, the electrical resistivity survey results delineated the first aquifer at an approximate depth range of 8m which falls within the phreatic zone. All small private boreholes tap groundwater from this aquifer.

IV. Materials and Methods

The work was carried out in two phases: field investigation and laboratory study. The field investigation consisted of geoelectric studies and borehole drilling. Electrical resistivity data were generated with the vertical electrical sounding (VES) technique using the Schlumberger configuration, with the aid of OYO-3964A terrameter as a quick appraisal tool to infer the lateral and vertical extent of hydrocarbon impact in the subsurface. [20], [21] and [22] indicated that VES techniques and results have recorded a huge success in the mapping of oil contaminated sites. Due to the swampy nature of the south eastern part of the site and solid fencing around the site which limited accessibility for wider electrode spread, a total number of eight (8) VES points were occupied using AB = 80m. The field data generated in the VES survey were interpreted for a one dimensional analysis using the IPI2-WIN resistivity software. Thereafter, a two-dimensional interpretation using RES2DINV software was applied to the geoelectric profiles. Also, subsurface conditions were studied by means of a post-hole auger sampler with extension rods, capable of sampling up to 5m. Soil samples were collected from five holes augered in the impacted area to the water table and from one borehole in an unimpacted area to serve as a control. Laboratory investigation consisted of determination of the engineering properties of samples of polluted and unpolluted soils from tests including moisture content, particle size distribution, Atterberg limits, unit weight, triaxial and oedometer consolidation test according to procedures specified by [23]. Soil pollution indices were determined using the method of [3] and [9], as the coefficient of the property of the polluted soil ($X_{polluted}$) to the unpolluted soil ($X_{unpolluted}$) expressed as

$$p_i = \text{pollution index} = X_{polluted} / X_{unpolluted} \quad (1)$$

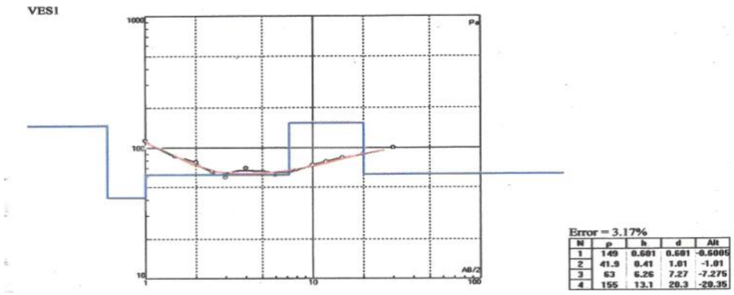
The significance of the changes in soil properties was derived by classification of the indices using the method of [24]. Soil pollution indices indicate the significance of impacts of spills on soil properties by measuring the presence of unnatural ingredients causing imbalances in the subsoil structure and eventually properties. The effect of pollution on the soil properties is of low significance if $Ip < 0.5$ but if $0.5 < Ip < 1.0$ then it is of medium significance. Index of high significant pollution effect is >1.0

V. Results

5.1 Soil Characterisation

The soil underlying the site are uniform and generally consists of brownish sandy silty clay and sand. Particle size distribution analyses by both wet and dry sieve analysis show that the soils are made up of 18 – 35% fines and 55 – 82% sand. The inorganic silty clay is of medium plasticity while the sand is mainly medium grained and well graded. Interpretation of the field resistivity data for VES 4, 5, 6 and 8 show H type curves (Fig. 2a) while VES 1, 3 and 7 yielded HA types (Fig. 2b). Only VES 3 shows the QH curve type (Fig. 2c). Four soil layers were generally delineated throughout the site from the geoelectric sections. For example, the geoelectric sections in the H-curves type delineated four soil layers with diagnostic evidence of hydrocarbon contamination. Hydrocarbon soaked topsoil with resistivity of 466Ωm occurs from the surface to a depth of 0.6m, succeeded by a second layer of hydrocarbon saturated clayey sand which is underlain by clayey soil in the third layer with a resistivity of 109Ωm to a depth of 7m. The fourth layer with a resistivity 145Ωm consist of sand down to a depth of 15m or more.

[25] used shallow borehole (5m deep) soil samples to measure the concentration of Total Petroleum Hydrocarbon (TPH) at 1m intervals in five boreholes drilled in the site. Results showed decreasing average TPH concentrations of 6000 ppm at 1m to 2000 ppm at 5m in the subsurface which is a direct indication of hydrocarbon contamination. This is at least 40 times the average background concentration of hydrocarbon in the region which is about 50 ppm. Similar pollution levels were obtained by {1}



N	ρ	h	d	Alt
1	149	0.601	0.601	-0.6005
2	41.9	0.41	1.01	-1.01
3	63	6.26	7.27	-7.275
4	155	13.1	20.3	-20.35

Fig. 2a: Resistivity curve of VES 1

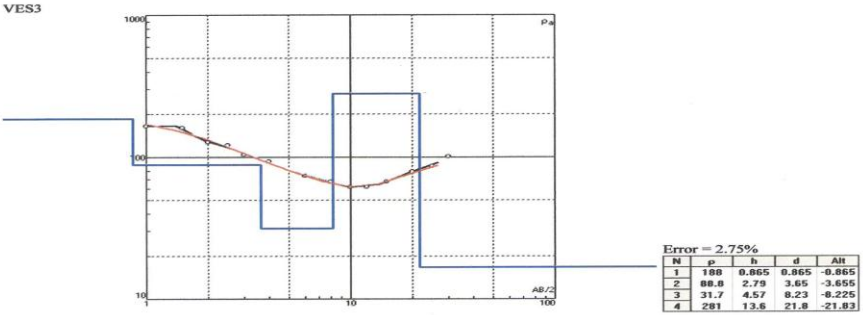


Fig. 2b: Resistivity curve of VES 3

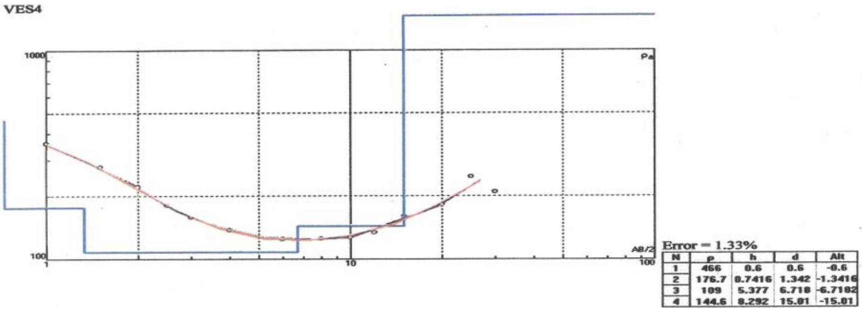


Fig. 2c: Resistivity curve of VES 4

Two dimensional representations of subsurface soils across the spill site and the control points are shown in Fig. 3. A maximum of three geoelectric layers were delineated. These include the topsoil from the surface to 0.8m, and comprising oil soaked soils with a resistivity ranges of 109Ωm-188 Ωm in the vicinity of BH 5 increasing to between 400 Ωm and 1134 Ωm around BH 3 and 4. A TPH value of 5714 ppm was obtained at this depth. The second layer is composed of silty clay saturated with hydrocarbon due to its characteristic resistivity lows (below 50Ωm in control VES 9). The presence of oil makes the second layer resistivity to appear as sand across the spill site (≥ 100 Ωm), and having a TPH values of 1500ppm approximately. The third sandy stratum with resistivity range of 145Ωm to 1322Ωm suggestive of hydrocarbon presence occurs at approximately 7 m, and is in the first aquifer of the study area. This sandy layer corresponds to the first regional aquifer.

5.2 Moisture Content

The moisture content of the unpolluted soils ranges from 20.18 % - 20.21 % with an average of 20.22% compared to that of the polluted soils which ranges from 18.06 % - 20.62 % with an average of 18.49 %. This shows a marginal decrease by 1.58% in the moisture content of oil polluted soils when compared with that of unpolluted soils (Fig. 4). The pollution indices in Table 2 classify the effect of crude oil on soil moisture content as potentially significant (PI < 0.5) which correlates well with the indices for Atterberg limits. However, pollution indices values at the centre of the spill represented by borehole one (1.02) and borehole two (1.14) are higher, indicating that impact of crude oil on the moisture content is significant around the central part of the spill site which corresponds to the source of the hydrocarbon leakage.

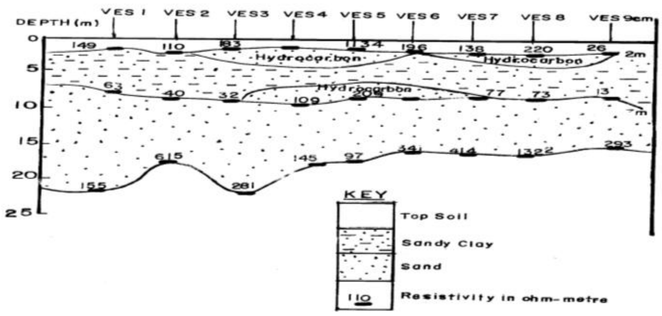


Figure 3 Subsurface soil profile of the spill site from VES data

5.3 Atterberg Limits

Generally, the soils classify as clays of low plasticity (CL) and medium plasticity (CI). The liquid limit of the unpolluted soils ranges between 39 % and 47 % while that of polluted soils falls between 37.33 % and 41.67 %. Similarly, the plastic limit of the contaminated soil marginally increased to values between 17 % and 27 % when compared to values of 21 % - 26 % for the uncontaminated soils. The plasticity index values showed the same marginal decrease from 14 % - 23 % for the polluted soils in comparison with 16 % - 21 % for the unpolluted soils. This clearly indicates that crude oil pollution lowers the Atterberg limits of soils (Fig. 5). The overall decrease in the Atterberg limits is approximately 8 %. The pollution indices associated with the Atterberg limits (Table 2) classifies the effect of pollution on the limits as potentially significant (0.7-1.0) and significant (1.0-2.0) respectively. The degree of significance is more evident in the central part of the study area due to the higher concentration of TPH in the soils. [13] explained that the presence of water around charged clay particles decreases when non -polarized liquid of oil occupies soils. The interaction between water and clay particles is hindered or completely removed when oil comes in contact with clay particles.

5.4 Shear Strength

The change in engineering properties of the soils was more significant in the shear strength parameters (Fig. 6) and consolidation coefficients. The undrained cohesion and frictional angle decreased in the polluted soils by an average of 22.92% and 27.78% respectively. The pollution index associated with the undrained cohesion (cu) and angle of friction (ϕ^o) is approximately 0.7. This classifies the effect of hydrocarbon pollution on the shear strength parameters as significant especially in the south-eastern and central portion of the study area. These results imply that the higher the oil in the soil, the lower the undrained cohesion. This can be explained that when oil comes in contact with soils, oil, which has a higher viscosity than water, will surround and create an oil blanket around the soil particles. Therefore, the oil content in the soil will increase the chance of inter-particle slippage and this will subsequently reduce the shear strength of the soils [13] which depends on cohesion and internal friction.

VI. Consolidation

The coefficients of consolidation (Cv), volume compressibility (Mv) and permeability (k) of the soils were obtained at different pressure ranges as shown in Table 3. Results obtained showed that the Cv of the soil generally decreases between 21 and 62% in the polluted soils with the more significant changes at higher pressure ranges of 200-800 kPa. The coefficient of consolidation (C_v) gives an indication of the likely rate of settlement over a period under given loading. This implies that it will take a longer time for consolidation to be achieved in the polluted soil. The coefficient of volume compressibility (M_v) which determines the area that is likely to be compressible under a given amount of load initially decreases between 3.45 and 8.10% at pressure ranges of 25-100 kPa, and thereafter increased by between 12.50 and 19.05 %. This indicates that for the polluted soils, less area will be consolidated compared to the unpolluted soils for a given period of time. Generally, the decrease in Cv is relatively more significant compared to the increase in Mv. However, the permeability of polluted soil estimated from oedometer test steadily decreased by between 14.81 to 50.46% as loading pressures increased. This corroborates the fact that when oil is introduced as the fourth phase of earth material, it coats the surrounding water, effectively reducing permeability. Similarly, during consolidation, soil volume decrease is accompanied by the expulsion of water in the void spaces. There is readjustment of the grain matrix resulting in densification of the soils as the particles pack more closely together. The concomitant effect is that the pore volume is considerably diminished, thus reducing the soil permeability, and resulting in longer times for the consolidation process to be completed.

Table 1 Geotechnical properties of the unpolluted soils

	Depth (m)					
Parameters	1	2	3	4	5	Average
Natural Moisture content (%)	20.21	20.31	20.20	20.21	20.18	20.22
Liquid Limit (%	44.00	47.00	41.00	39.00	42.00	42.60
Plastic Limit (%	24.00	26.00	21.00	23.00	23.00	23.40
Plasticity Index (%	20.00	21.00	20.00	16.00	19.00	19.20
Bulk unit weight (kN/m^2)	19.71	19.71	18.81	19.71	19.61	19.51
Cohesion (kN/m^2)	42.00	43.00	40.00	40.00	40.00	41.00
Internal friction (^{o})	3.00	4.00	3.00	4.00	4.00	3.60

Table 2. Geotechnical properties of the polluted soils

Depth	**1m**	**2m**	**3m**	**4m**	**5m**	**Average (Unpolluted Soils)**	**Average (Polluted Soils)**	**% decrease**	**Pollution Index**
Natural Moisture content (%)	20.62	23.23	18.06	19.08	18.49	20.22	19.90	1.58%	0.98
Liquid Limit (%	41.67	40.00	39.16	37.33	37.50	42.60	39.13	8.15%	0.92
Plastic Limit (%	24.17	22.75	20.33	20.33	19.33	23.40	21.38	8.63%	0.91
Plasticity Index (%	18.17	17.50	19.32	17.33	17.67	19.20	18.00	6.25%	0.94
Bulk unit weight (kN/m^2)	19.93	19.59	19.37	19.27	19.17	19.51	19.47	Negligible	1.00
Cohesion (kN/m^2)	22.00	20.00	31.00	42.00	43.00	41.00	31.60	22.92%	0.77
Internal friction (^{o})	2.00	2.00	3.00	3.00	3.00	3.60	2.60	27.78%	0.72

Table 3 Average consolidation coefficients of the soils

Pressure Range (KPa)	**Coefficient of consolidation Cv (m^2/yr)**			**Coefficient of volume compressibility, Mv (m^2/MN)**			**Permeability, K (m/sec) $x10^{-8}$**		
	Unpolluted soils	Polluted soil	% decrease	Unpolluted soils	Polluted soil	% decrease	UnPolluted soil	Polluted soil	**% decrease**
25-50	9.6	10.6	5.10%	0.37	0.34	8.10%	10.8	9.20	**14.81%**
50-100	11.07	8.11	26.74%	0.29	0.28	3.45%	9.84	6.47	**34.25%**
100-200	9.88	7.8	21.05%	0.21	0.25	19.05%	3.63	1.98	**45.45%**
200-400	11.47	4.29	62.60%	0.13	0.16	23.08%	3.63	1.98	**45.45%**
400-800	**5.29**	**2.04**	**61.43%**	**0.08**	**0.09**	**12.50%**	**1.09**	**0.54**	**50.46%**

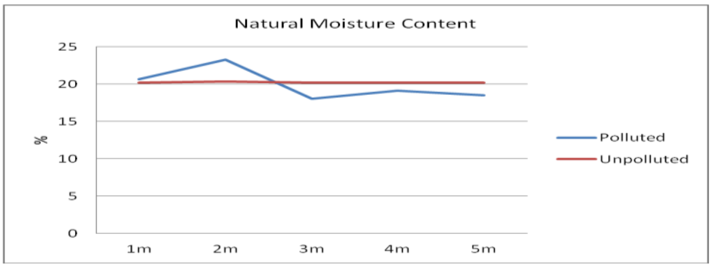


Figure 4 Change in moisture content

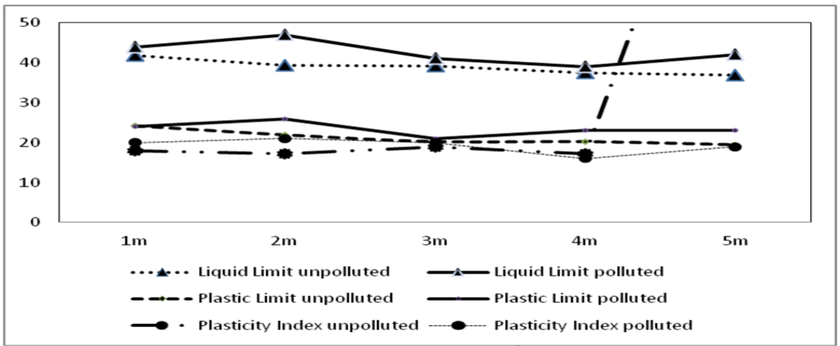


Figure 5 Change in values of Atterberg Limits

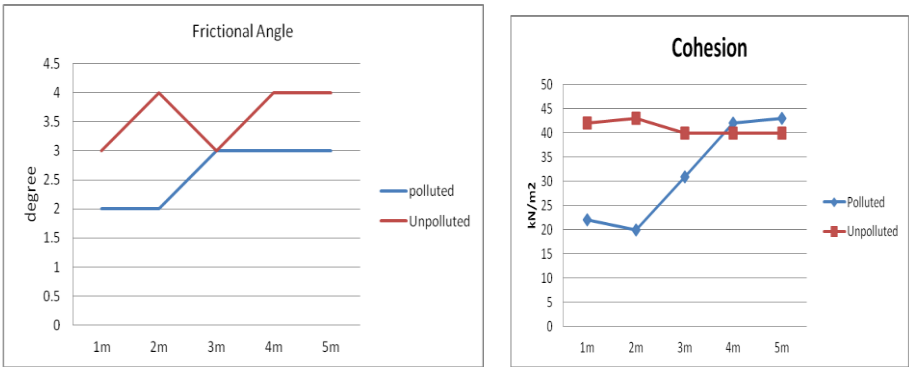


Figure 6 Variations in values of shear strength parameters

VII. Discussion

The magnitude of modification of the soil properties can be inferred from the pollution indices which range from 0.72 to 0.98 and classify as changes of high significance. The change in engineering behavior of soils can be related to the change of its fabric as a result of hydrocarbon contamination ([26], [27]. Naturally, particulate earth materials are a three phase system of solid particles, voids and water. The presence of oil introduces a fourth phase. According to [28] when pollution of soil occurs, electrostatic repulsive forces in the polluted samples are much lower than in non-polluted samples. Thus, oil, like water, increases the chance to inter-particle slippage and reduces the shear strength parameters of the soils when it introduces a fourth phase into the natural three phase system of particulate earth materials. The values of the compressibility coefficient of polluted soils tend to be low while that of unpolluted soils remain high. It may be adduced that an old oil spill site exhibits low settlements due to biodegradation, precipitation, geologic and human activities. In contrast, soils from a fresh spill site have been found to have large compressibility [3]. Soils in the north-western and south-eastern flank of the spill site have undergone relatively more significant changes in the index properties. These flanks correspond to the alignment of the crude oil transportation pipeline which is the origin of the pollution plume. Soil samples recovered from the boreholes located along this axis yielded highest TPH concentrations. These results have clearly confirmed that oil contamination on soil system has a great influence on the geotechnical properties of the soils by modifying them. Results of this study are in agreement with findings of [4] and [9]) who found that whenever soils are polluted by crude oil or any of its derivatives, the soil properties are generally affected especially the shear strength parameters of cohesion and frictional angle.

Following from the results of this study, and in agreement with [9], it can be stated that as a derivative of equation 2, the Mohr-Coulomb shear strength (τ) of polluted soils may be expressed as

$$\tau = (c)\,(cpi) + \sigma \tan(\text{Ø}.\text{Ø}pi) \qquad (2)$$

Where:

c_{pi} = Cohesion pollution index = $C_{polluted} / C_{unpolluted}$

Ø_{pi} = friction angle pollution index = $\text{Ø}_{polluted} / \text{Ø}_{unpolluted}$

Also the allowable soil bearing capacity of polluted clayey soil will be lowered according to the relationship

$$q_a = (c).\,(c_{pi}).\; Nc \,/\, F.\,S \qquad (3)$$

Where:

F.S = Factor of safety

c_{pi} = cohesion pollution index

Nc = Terzaghi's bearing capacity factor with respect to cohesion.

Similarly, for cohesionless sandy soils, the reduced allowable bearing capacity becomes

$$q_a = q_{ult} / FS = \{0.5\gamma\,(\gamma_{pi})N_\gamma + \gamma\,(\gamma_{pi})\,(N_q - 1).D_f / B\}B/FS \qquad (4).$$

Where:

γ_{pi} = density pollution index = $\gamma_{polluted} / \gamma_{unpolluted}$

N_γ = Terzaghi's bearing capacity factor with respect to density.

N_q = Terzaghi's bearing capacity factor with respect to imposed loads.

B= width of foundation

F.S = Factor of safety.

Since N_γ and N_q are dependent on angles of internal friction (Ø) of soils which are significantly lowered by crude oil pollution, the corresponding values of N_γ and N_q for polluted soils will also be lowered, thus giving an overall lowered soil bearing capacity for sandy soils as given in equation (4).

VIII. Conclusions

The soil underlying the area is uniform in lithology, consisting of clayey sand. The effect of oil contamination on some geotechnical properties were clearly observed on the subsoils from results of electrical resistivity surveys and laboratory tests. 2-D electrical imaging gave very low resistivity (38 - 220Ωm) at about 7m which is within the depth of the first aquifer in the region, indicating possible contamination of the shallow water bearing soils. The Atterberg limits of polluted soils were lower than that of unpolluted soils. Similar behavior was also observed on permeability and shear strength of the contaminated clays/soils. Soils polluted by hydrocarbon have oil film surrounding the original water film, thereby ensuring stronger bonding forces. The adsorption effectively reduces soil engineering properties, e.g. permeability is reduced by repelling water from the surface of the soil grains. The results have clearly showed that oil contamination on the soils have significantly worsened their geotechnical properties. A recognition of the significant changes in soil properties at oil spill sites will ensure safe and adequate design of foundations at such locations.

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