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Effect of Crude Oil Contamination on the Geotechnical Properties of Soft Clay Soils of Niger Delta Region of Nigeria

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ABSTRACT

This paper presents the results of recent study on the effect of crude oil contamination on the geotechnical properties of soft clay soils of Niger Delta region of Nigeria. Laboratory investigation was carried out to compare selected engineering properties of uncontaminated and oil-contaminated soft clays. The effect of contamination by crude oils from three oilfields on the engineering properties of soft clay soils has been studied. Crude oil was chosen as the contaminant. Soil samples around three oilfields as well as crude oil samples from selected oil wells in these fields were randomly collected and investigated. The oil wells are located in Bonny, Brass River and Qua-Ibo communities respectively. A comprehensive laboratory investigation was carried out on the collected samples at the field dry density of 14 kN/m^3. Contamination of soft clays by crude oil caused 17.9% increase in the Liquid limit, 6.9% increase in Plastic limit and 37.5% increase in plasticity index. It also showed corresponding increase in Bulk Density with increase in sorption time. However, porosity and swelling pressure of contaminated clay decrease with increase in both sorption time and crude oil content, while its undrained shear strength fluctuates.

KEYWORDS: Crude Oil Contamination; Soft Clay Soils; Geotechnical Properties; Swelling Pressure; Porosity.

INTRODUCTION

When oil is spilled intentionally or unintentionally, the immediate and remote environment, including the soils, is contaminated. The contaminated soils are not only a challenge for the environmentalists but also for the geotechnical engineers. Clay soil being electro-chemically active is mostly affected whenever the environment is contaminated by fluid substance (Habib-ur-Rehaman *et al.*, 2007). Oil pollution due to spill could take place in water or on land. Crude oil pollution on land depends on a number of factors which include; the permeability of the soil, adsorption properties of the soil and the partition coefficient (Nudelman *et al*., 2002). The extent of contamination depends on the chemical composition of the contaminant and the properties of the soil (Fine *et al*., 1997).

Hydrocarbon pollution of soil can occur in several ways, from natural seepage of hydrocarbons in areas where petroleum is found in shallow reservoirs, to accidental spillage of crude oil on the ground. Regardless of the source of contamination, once hydrocarbons come into contact with the soil, they alter its physical and chemical properties. The degree of alteration depends on the soil type, the specific composition of the hydrocarbon spilled and the quantity spilled. Once a spill or a leakage occurs, the hydrocarbon liquid, under gravity, moves down to the groundwater, partially saturating the soil in its pathway (Tuncan and Pamukcu, 1992). Upon reaching the groundwater table, this liquid may spread horizontally by migration within the capillary zone, thereby further saturating the soil. Clay particles are chemically active soil particles. Their behavior is always affected by the environment to variable degree depending on the clay particles' mineralogy. The particular environment includes the pore fluids and their properties and type of ions present therein (Lagaly, 1987).

Oil production in ogoniland, Niger Delta region of Nigeria (fig. 1) started in 1958. Between 1976 and 1990, oil companies in Nigeria reported a total of 2,796 oil spills. An estimated total quantity of 2,105,393 barrels of oil was spilled on land, coastal and offshore marine environments (Kontagora, 1991). In 1974, an extensive oil spillage occurred near Ebubu-Ochani area in Gokana LGA, Rivers State, Nigeria (fig. 2). It was from an oil delivery pipeline that busted off a petroleum flow-station. The spilled oil caught fire. Incineration of the spill on soil surfaces resulted in the formation of tar mat oily scum. This may have prevented soil aeration and water infiltration into subsoil layers (Amadi *et al*., 1996). In May 2000, an oil pipe leakage occurred at the Diebu Creek Field, a freshwater environment in the Niger Delta area of Bayelsa State, Nigeria (Daniel-Kalio and Braide, 2004). There are several reasons for the huge number of spills, including crumbling, aging oil infrastructures and outright sabotage by thieves and warring rebel groups. The recent spill at Bonga oilfield off the Nigerian coast of Niger Delta, and many unattended devastating crude oil contamination of soil and other environmental media call for attention and analysis.

In connection with the cleanup works, and for any possible applications of contaminated soils, knowledge of the geotechnical properties and behavior of contaminated soil is required. This information is also required when oil leakage from storage tanks and processing plants cause oil contamination in the surrounding soils. In this case, necessity to determine the effect of oil contamination on clays soils in selected areas of Niger Delta region of Nigeria provoked this research.

This paper therefore presents the results of field and laboratory study carried out to determine effect of crude oil contamination on geotechnical properties of soft clay soils taken from three oilfields in Niger Delta region of Nigeria where crude oil spills have occurred. Some of the properties investigated include Atterberg limits, strength parameters (Triaxial compressive strength and direct shear tests), compaction characteristics, porosity and swelling pressure.

Figure 1: Map of Nigerian Niger-Delta Oilfields

Figure 2: Oil spill at K-Dere, Gokana LGA, R/S.

EXPERIMENTAL INVESTIGATION

The soils used in this study were soft clays samples obtained around three oil wells located in Bonny, Brass River and Qua-Ibo respectively, all in Niger Delta region of Nigeria. Oil-contaminated clay near the oil wells and uncontaminated clay samples were collected from the said oilfields. Crude oil samples were also collected from the oil wells. A total of 72 soil samples (24 from each oilfield) and 18 crude oil samples (6 from each oil well) were randomly collected from the three designated oilfields. The soil samples were air-dried for one week in order to stimulate field environmental condition, and thoroughly pulverized thereafter. Predetermined quantities of these oils were mixed the pulverized soft clay soil at its natural dry density of 14 kN/m3 until the samples were fully saturated. Using crude oil of grades 35 (Bonny light of 350 API gravity), 36 (Brass River of 360 API gravity) and 36 (Qua-Ibo of 360 API gravity) respectively as the contaminants, a comprehensive laboratory investigation was then carried out on the conditioned contaminated soft clay in order to determine the effect of crude oil contamination on its geotechnical properties. Laboratory investigations conducted on clean (uncontaminated) as well as oil-contaminated soft clay to determine geotechnical properties include:

- Crude oil characterization using Gas Chromatographic (GC) method and ASTM method;
- Evaluation of Atterberg limits of samples (ASTM D423, D424 and D427);
- Investigation of compaction characteristics using Standard Proctor compaction test (ASTM D698);
- Strength evaluation of samples by Unconsolidated Undrained Triaxial compression tests on cylindrical specimens 51 mm in diameter and 102 mm long (ASTM D-2850);
- Sorption test to investigate contaminant effect on bulk density and porosity;
- One dimensional consolidation test on samples 70 mm in diameter and 191 mm in thickness, for compressibility test according to (ASTM D-2435);

- Standard constant volume One-Dimensional swell tests on statically compacted soft clay samples according to (ASTM D4546-08).

DISCUSSION OF TEST RESULTS

Crude Oil Classification

The crude oil characterization was carried out based on the hydrocarbon fractions of the n-alkanes of various crude oil types, viscosity, API gravity and density. The values for the total hydrocarbon content (THC) of the crude oil samples are ***1082.1141***, ***1289.4997*** and ***1124.0562*** ppm, for Bonny, Qua-Iboe and Brass River oil wells respectively. This result seems to be in agreement with the study of (Uzoije and Agunwamba, 2011).

Geotechnical Properties

The geotechnical properties used to investigate the influence of microstructure and physico-chemical changes on the physical and mechanical behavior (engineering properties) of soft clay under investigation were determined for both the uncontaminated and oil-contaminated soft clays soils. The summary of various properties investigated are shown in Table 1.

Table 1: Summary of Selected Properties of Uncontaminated and Contaminated Clays.

Property	Uncontaminated Soft clay	Contaminated Soft Clay
Liquid Limit (%)	67	79
Plastic Limit (%)	43	46
Plasticity Index (%)	24	33
Shrinkage Limit (%)	18	21
Compression Index (%)	0.312	0.851
Swell Percentage (%)	27.7	28.3
Swelling Pressure (kPa)	594	182
Max. Dry Density (kN/m^3)	14.1	16.7
Opt. Moisture Content (%)	22.8	8.3

Atterberg Limits

As shown in Table 1, addition of crude oil caused 17.9% increase in the Liquid limit, 6.9% increase in Plastic limit and 37.5% increase in plasticity index. The increase in cohesion of contaminated clay must have been caused by the increase in bonding by oil particles. Hence, additional water would be required to cause a change in consistency level for a thick layer of contaminated clay.

Compaction Test (Moisture-Density Relationship)

With the crude oil acting as lubricant in the contaminated soft clay, Standard Proctor test (ASTM D2850-03a; 2007) was carried out on the samples. The test revealed a marked increase in maximum dry density at relatively low optimum moisture content in contaminated soft clay against the uncontaminated as shown in both Table 1 and Fig. 3.

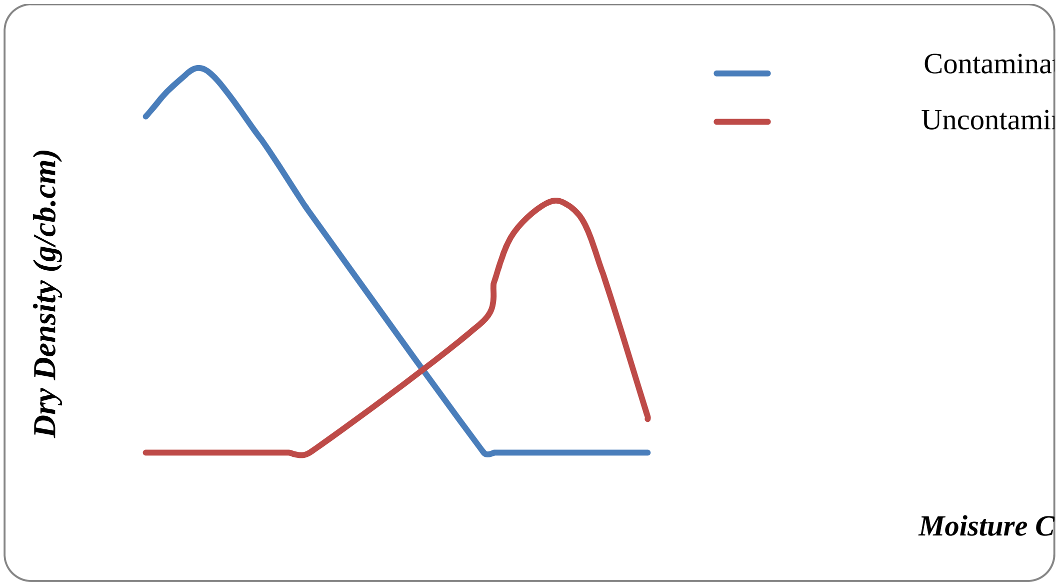

Figure 3: Moisture-Density relationship for the Uncontaminated and Contaminated Clays

Shear Strength

Unconsolidated undrained triaxial compression test was carried out on the soft clay soil to investigate its strength. The size of the sample used for the strength tests was 51 mm in diameter and 102 mm long. The samples were compacted at the field dry density of $14kN/m^3$. As shown in Fig. 4, the strength of the contaminated soft clay at low confining pressures was less than that of the uncontaminated one, while at high confining pressures; the strength was slightly higher than that of the uncontaminated one. The increase in the strength of the crude oil contaminated soft clays could be attributed to the agglomeration of its particles in the presence of oil.

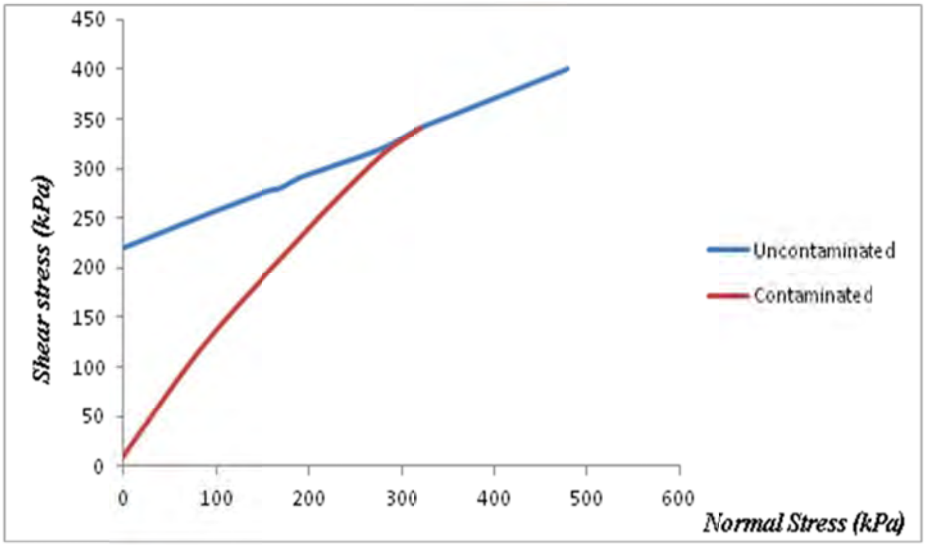

Figure 4: Mohr-Coulomb Envelopes for Uncontaminated and Contaminated Soft Clays

Sorption Test

Sorption test was carried out for the clay samples with crude oil samples from the three oilfields of Bonny, Brass River and Qua-Ibo oil wells respectively. With soft clay soils as the adsorbent media, varying quantities of crude oils from the designated oil wells were tested for sorption with contact time of 1, 2, 3, 4 and 5 months. From the results shown in Fig.5, sorption processes with light crude oil samples that is, crude oil samples with low amount of molecular total hydrocarbon contents (THC, in this case Bonny crude oil, then Qua-Iboe crude oil), impacted lower density values on the soft clay soil than the heavier crude oil samples (Brass River crude oil). The variations of soil bulk density observed after the sorption process with various crude oil samples could be attributed to different values of the total hydrocarbon content of various crude oil samples and the impact on soft clay soil's bulk density was as a result of varying values of the Total Hydrocarbon Content (THC) inherent in each crude oil. These observations seem to be in agreement with the study of (Ogboghodo *et al*. 2004).

Concerning porosity, as shown in Fig.6, as the sorption time increases the porosity of contaminated soft clay soils decreases. The effects could be attributed to the reduction of pore sizes of the clay soil by the adsorbed hydrocarbons. It can also be deduced from here that, soil texture and crude oil hydrocarbon contents influenced the observed changes in the porosity of contaminated clay soils.

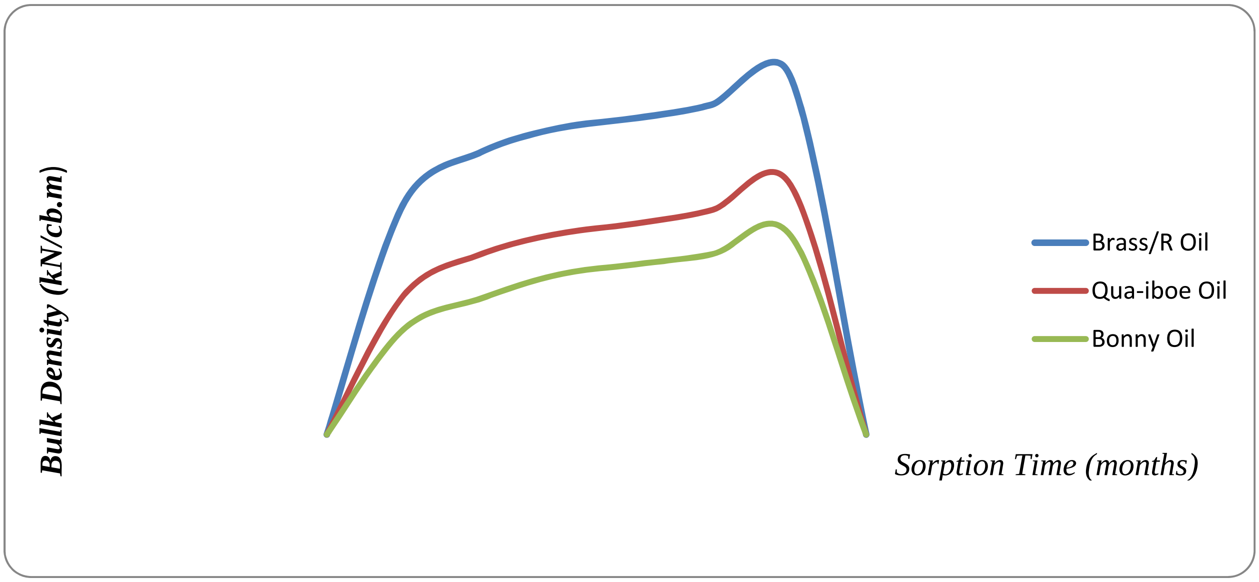

Figure 5: Bulk density variation with Sorption Time on application of Crude oil samples on Clay.

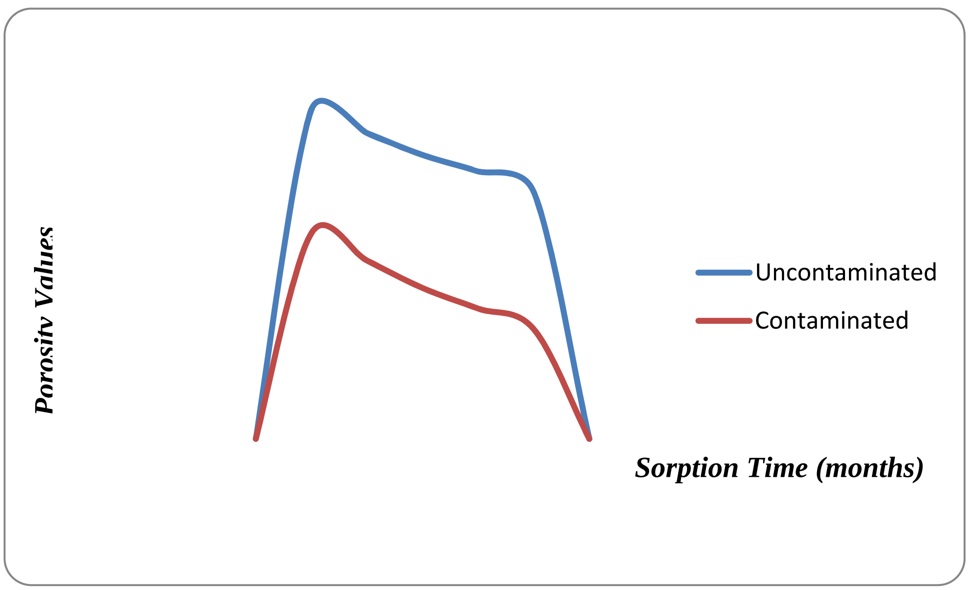

Figure 6: Porosity variation with Sorption Time of Uncontaminated and Contaminated Clays

Compression and Swelling Characteristics

One dimensional consolidation test was carried out on both uncontaminated as well as oil-contaminated clays to investigate its compressibility using ASTM D2435 method. A consolidation ring of 70 mm diameter and 191 mm height was used in the testing. Experimental

Clay samples for consolidation, swelling and swelling pressure tests were prepared at the field dry density of 14 kN/m^3.

Samples prepared at this density (14 kN/m^3) were allowed to swell under a surcharge pressure of 8.2 kPa. As shown in Fig. 7, the rate of swelling at the initial stages was higher for uncontaminated clay. But despite the fact that the rate of swelling in oil-contaminated clay was much less than in the uncontaminated samples, the total swell percentage observed remained the same. This seems to agree with the study of (Habib-ur-Rehman *et al*., 2007).

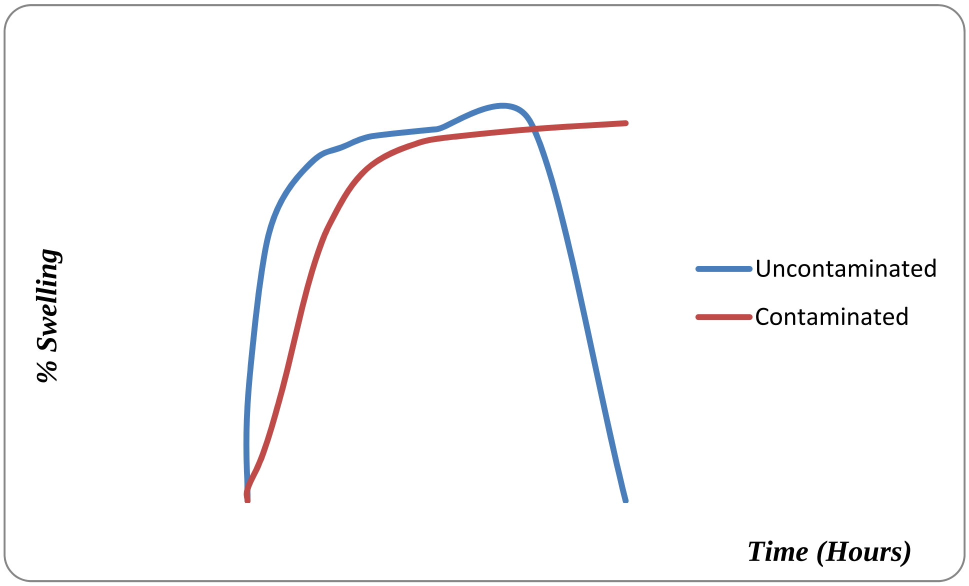

Figure 7: Percentage Swelling for Uncontaminated and Contaminated Clays

Swelling Pressure Test

Standard constant volume One-Dimensional swell tests (ASTM D4546-08) were performed on statically compacted uncontaminated as well as oil-contaminated soft clay samples. The tests were conducted at the field dry density of the soil in standard oedometer cells. The volume of the sample was kept constant by being inundated by water. The swell pressures of each specimen with known plasticity indices and initial water contents were then measured in the loaded cells of the oedometer. The results shown in Fig. 8 revealed that the swelling pressure exerted by oil-contaminated soft clay was far less (about 32%) of that exerted by the uncontaminated clay.

CONCLUSIONS

The following conclusions are drawn from the tests conducted:

- Crude oil contamination of soft clay leads to a marked increase in maximum dry density at relatively low optimum moisture content;
- The constitution of various crude oil samples has appreciable influence on the geotechnical properties of soft clay soils and the sorption process. Light crude oil samples (i.e. with low THC), impact lesser influence on the bulk density and porosity of soft clay soils than heavier ones;

- At high confining pressures, the strength is relatively high, indicating the dependency of the strength of contaminated soft clay on confining pressure;
- Crude oil contamination induces a reduction in permeability and strength of soft clay soils. Soil texture and crude oil hydrocarbon contents influenced the observed changes in the porosity of contaminated clay soils;
- The bulk density of oil-contaminated soft clay soil increased linearly with sorption time, while its porosity of decreases with increase in sorption time;
- The swelling pressure exerted by the oil-contaminated soft clay was far less (about 32 %) of that exerted by the uncontaminated soft clay.

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