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Geotechnical properties of shallow marine sediments, offshore Olokola, Nigeria

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Abstract

Oil and gas Exploration and Production operations in Nigeria is rapidly shifting to the shallow offshore section of the continental shelf following prolific hydrocarbon finds in the area and increased militancy in the alternative onshore locations. This is besides the significant military, civil and scientific applications that are possible in this environment. Offshore operations experience considerable geotechnical challenges which are better understood and resolved with improved understanding of the geotechnical properties of the shallow marine environment. This study investigates the spatial distribution and potential trends of pertinent geotechnical properties within the offshore corridor of Olokola, covering an area in which a total pipeline network of 463km runs. The results indicate that the value of pertinent geotechnical parameters vary systematically and appears to be governed by trends to a large degree, suggesting an overwhelming influence of vectors such as tidal currents and waves in the distribution of shallow offshore sediments. The spatial variation of each parameter has been characterized.

Keywords: Geotechnical properties, shallow marine, offshore, Nigeria

1 Introduction

Relatively few studies have focused on the geotechnical properties of sediments encountered during dredging, construction of pipelines or drilling in the shallow offshore area of Nigeria. Near surface seafloor properties are needed for recreational, commercial, and military applications (Harris et al 2012). The military for example is interested in a variety of seafloor properties such as bearing capacity, time-dependent settlement, and stability of objects on the seafloor. Civil applications; anchorages and moorings depend on sediment properties as does the mobility of equipment designed to traverse the seafloor. Construction projects on the ocean seafloors often require extensive knowledge about strength, deformability, hydraulic, thermal, acoustic, and seismic characteristics for locating stable environments and ensuring proper functioning of structures, pipelines, and other installations on the surface of and buried into the marine sediments.

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Geotechnical properties provide a lithological and geotechnical description of the sediments in a way that issues relating to composition of the depositional environment and submarine slope stability are brought into focus. Generally, physical properties of marine sediments are good indicators of the composition, microstructure and environmental conditions during and after the depositional process (Kim et al 2007, Tenzer and Gladkikh 2014). These properties have also served as proxy parameter for geological or paleoceanographical processes and changes in the environmental conditions. Furthermore, physical parameters which quantify the amount and distribution of pore space or indicate alterations due to diagenesis are important in predicting the behavior of marine sediments when loaded. Porosities are necessary to calculate flow rates, permeabilities describe how easy a fluid flows through a porous sediment and help in understanding consolidation settlement rates. Atterberg limits indicate current soil state and potential behavior if disturbed through excavation. This high interdisciplinary value of physical property measurement results from the different effects of changed environmental conditions on sediment structure and composition.
Construction of pipelines, foundations of platforms and jackup rigs are some of the geotechnical activities within the shallow offshore that require geotechnical information of the seabed. Marine surveys can be used to characterize the seabed in a manner that should anticipate the challenges of pipeline placement at shallow depths below seabed.

2 Description of Study area

The study area lies offshore of Olokolo, Ogun state, Nigeria (Fig. 1), an area dominated by Tides, winds and currents.

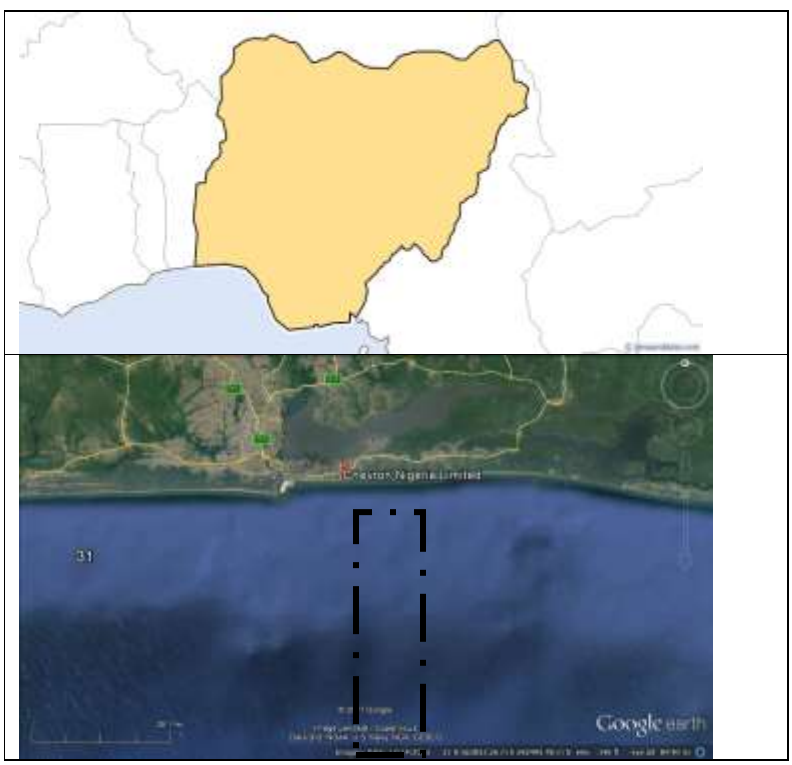


Fig. 1: The study area

2.1 Tides, Ocean currents and Wind

According to RIDER (2004) anywhere from 20 to 80% of the energy of those currents is tidal. The tides affecting the study area are semi diurnal with two inequalities. The spring tidal range is about 1.5m and significant surges are infrequent. The most energetic currents over this shelf are semi-diurnal tides (Fig. 2). The semi-diurnal signals account for 90% of the total tidal variance averaged over both shallow and deep sites; shallow sites contain slightly more diurnal energy than the deeper sites. Tidal energy accounts for 25-50% of the energy of surface currents and 30-80% of that of the bottom currents.

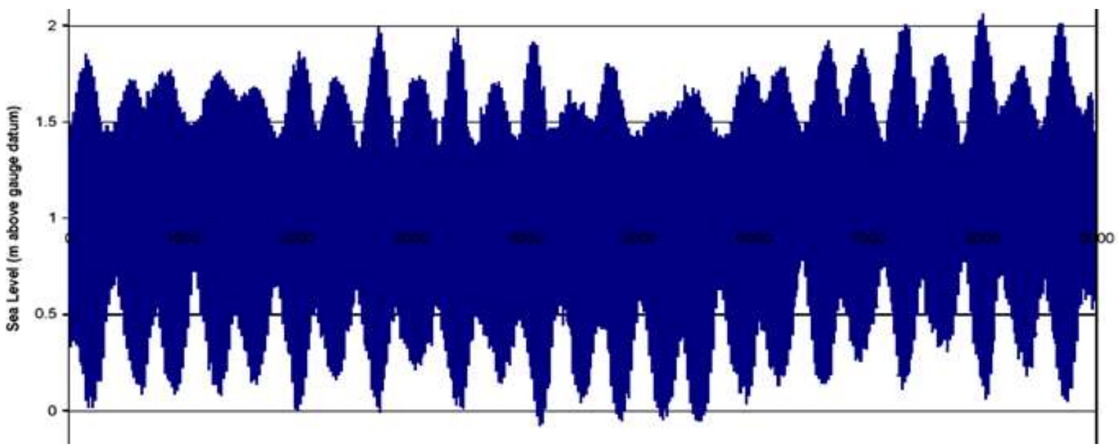


Fig. 2: Tide Gauge Data 26/11/02 to 06/12/03 in nearby Brass (Brass NLNG EIA 2006)

The Guinea current is the major oceanic current affecting the Brass area. The Guinea Current flows east at approximately 3°N along the western coast of Africa (Henin et al. 1986). When it reaches the Gulf of Guinea, it can attain velocities close to 100 cm s^{-1} near 5°W (Richardson and Reverdin 1987).

Ocean current data from Acoustic Doppler Current Profiller installed at two locations offshore Brass (both near to the NAOC "SBM – SIRUS" offshore facility for the period of 1 year showed maximum measured depth averaged currents to be 0.7-0.8ms-1 at Location-1 and 0.6-0.7ms-1 at Location-2 **(Brass LNG EIA 2006)**. In both cases the maximum currents were in the 75_-105^{0}_-direction sector. Maximum measured currents in the whole year were observed at the surface, with magnitude 1.1ms-1. The waves arriving along the east - west trending coastline arrive obliquely to the coast and hence produce a west-east longshore current. The major near-shore drift cells affecting the area consist of a west-east littoral cell of the eastern Niger delta. Fig. 3 shows wave pattern, comprising the directions and wave height through the year.

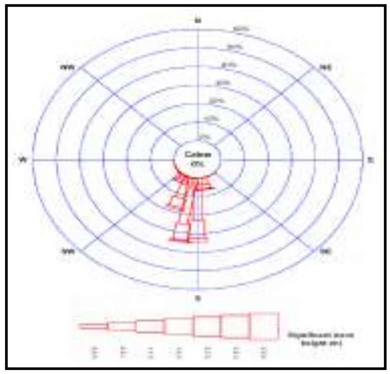


Fig. 3: The Wave pattern around study area

The wave distribution shows an almost identical pattern because of the heavy dependence of waves on the wind. The prevailing winds generally along the coastal area of Nigeria are a persistent southwesterly monsoon throughout the year (Fig. 4). Annual wind speed vary between 2 to 6 m/s in the study area (Brass LNG EIA 2006). They are strongest from July to September, due to movement of the intertropical convergence zone. During the rainy seasons (June to July and September to October), wind speed could peak to about 14m/s. Winds during the wet season are stronger on average than the dry season with August experiencing the strongest average winds.

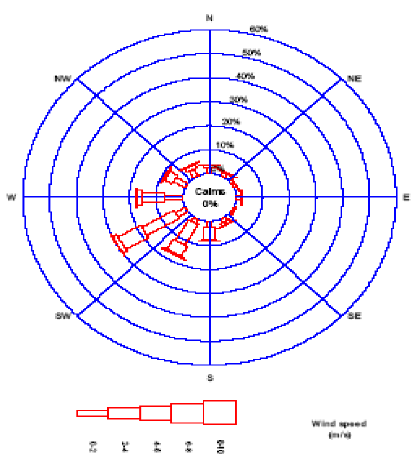
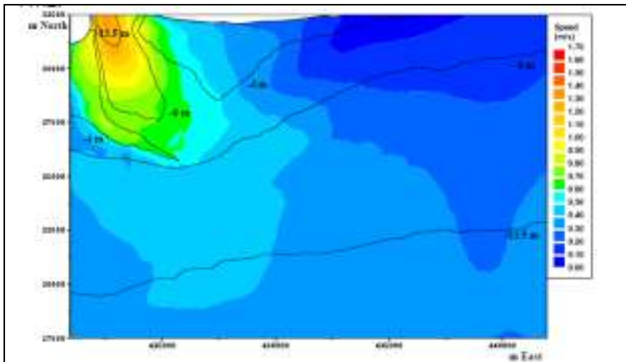
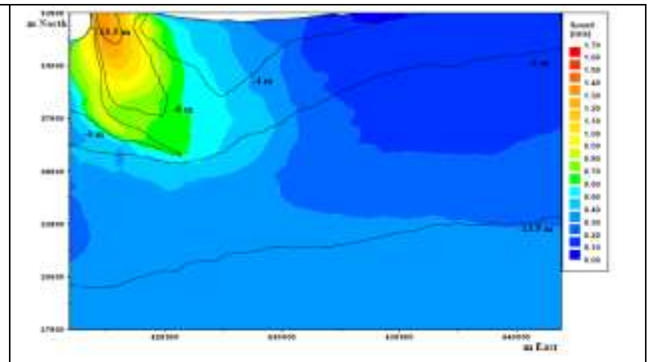


Fig. 4: Wind Rose Data for Annual Wind Conditions Measured at Onshore Meteorological Station in nearby Brass

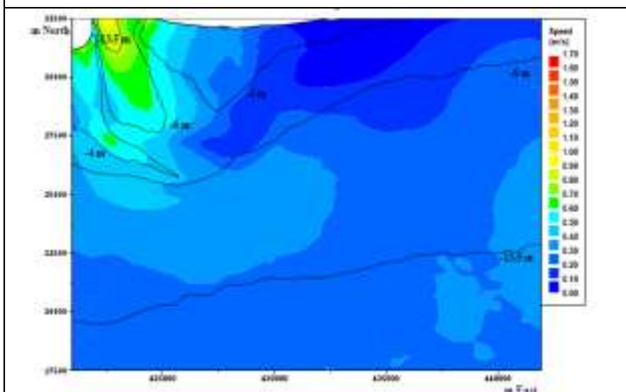
Analysis of the currents in nearby Brass area (Fig.5) gain insight to a better understanding of their effects in the dispersion of suspended sediments in the area. The contour lines of the surface currents indicate that they run almost perpendicular to the shoreline.



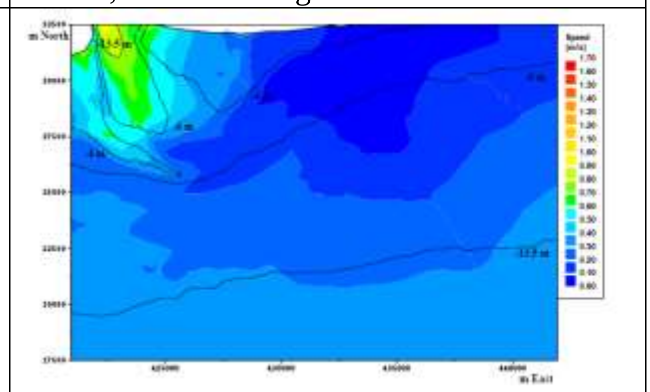
Current condition at peak ebb for dry season



Surface current magnitudes at peak ebb, wet season, 1.5m tide range- Wet season



Current condition at peak flood dry season



Surface current magnitudes at peak flood, wet season, 1.5m tide range - Wet season

Fig. 5: Current conditions around study area

Longshore currents also operate within the coastal waters of Olokola. The longshore currents which are comparatively weaker than the tidal current consist of a west - east longshore current direction tends to disperse sediments transported by tides and waves. The fact that the waves breaking along the coastline arrive at oblique angles to the coast, and the generated longshore currents move predominantly in a west- easterly direction result in the formation of a west- east littoral cell. Longshore currents in this area attain speed-averaging 0.2m/s (Rider 2004).

3 Data Acquisition

Data acquisition had both field sampling and on-board and laboratory testing components. The equipments used for the on-board geotechnical investigations included: Gravity corer, Minivane, Pocket Penetrometer and Grab sampler. The traverse pattern is shown in Fig. (6).

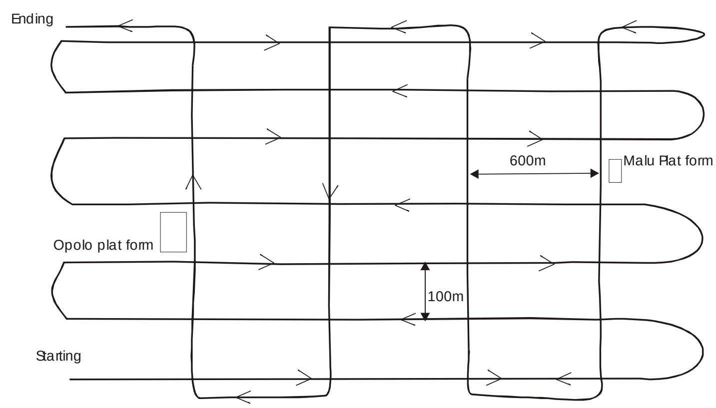


Fig. 6:Traverse pattern during marine surveys

I The spacing for the straight lines is 100m apart
II The spacing for the crossing lines is 600m
III This survey is through the rout opolo to malu platforms
IV GPS Co-ordinates are taken as we move along the lines

The gravity corer was deployed to obtain undisturbed core samples up to a maximum sample thickness of 6m below seabed. However, due to operational reasons, coupled with limited available space in vessel and soil stiffness, such long core barrels which are as high as the A-frame were not advised. For these reasons, the depth of cores was limited to 1m below seabed. All recovered core samples were tested on board before they are immediately sealed in order conserve the structure and moisture conditions of the soil pending the determination of the soil properties in the offsite laboratory.

The grab sampler was used to obtain seabed soil samples. In this particular exercise grab sampling was carried out at every 500m interval in every route of the surveyed area. Each sample was adequately described. Core samples were in addition to routine geotechnical description subjected to on-board testing, using Minivane shear tester and Pocket Penetrometer. Upon return from the field, all samples were taken to the laboratory for further tests and analyses.

A series of classification and strength tests were carried out on the samples recovered from the cores. The tests were performed strictly in accordance with the British standards (BS 1377 of 1990) and included: Moisture Content, Atterberg Limits, Bulk Unit Weight, Dry Unit Weight, Unconsolidated Undrained Triaxial Compression Test, Laboratory Vane shear Test, Particle Size Distribution, Organic Carbon and Carbonate Content.

4 Results and Discussions

The continental shelf in the study area reveals some undulations in seabed topography. A linear profile through the area however, shows a gentle slope around the shoreside. The slope becomes progressively uneven until the 300,000 latitudes, which occurs some

30km from the shoreline, where the bathymetry begins to experience a sharper gradient. This sharp decent in seabed topography is also noticeable in the satellite imagery (Fig. 1) and reflects a more rapid decent in seabed elevation (Fig. 7). On the average, the slope of the continental shelf within the study area is 6.07×10^{-5}.

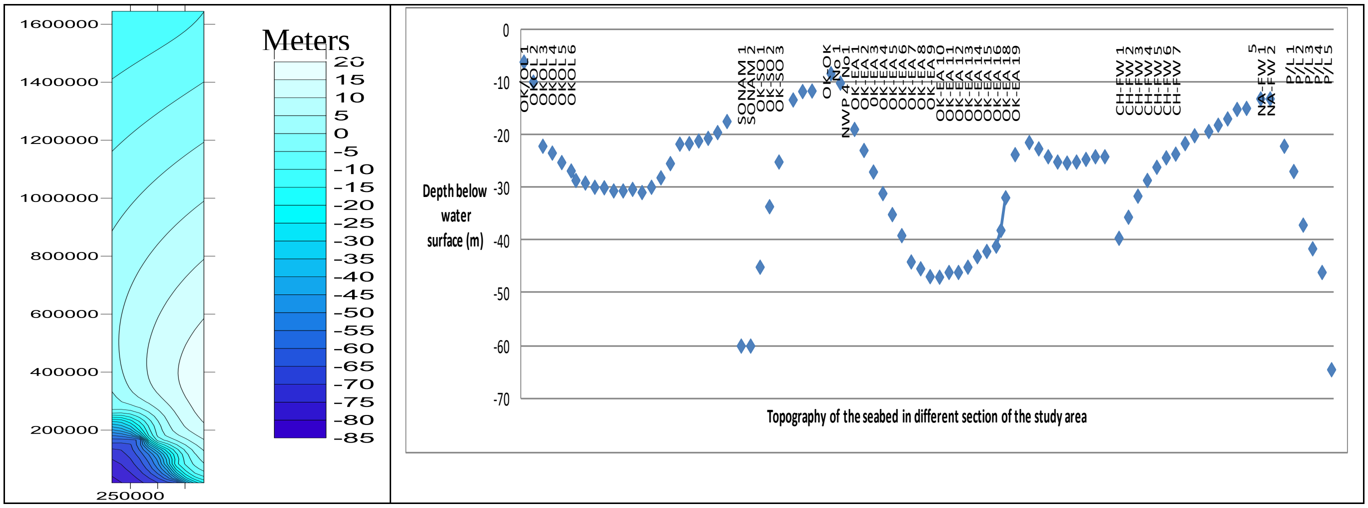
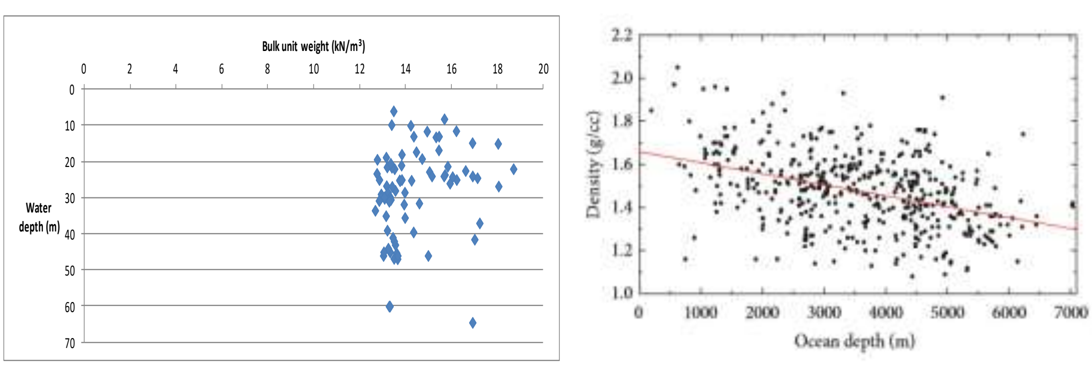


Fig. (7) Bathymetry of the different sections of the study area

A summary of the geotechnical properties of the soils at the site is presented under results. The sediments within the study area consists essentially of medium to extremely plastic clay sediments, mostly in semi-solid state, indicated by natural moisture contents that are higher than the liquid limits. The percentage organic content, organic matter and carbonate are all generally below 10%. The electrical conductivity is high and reflective of the marine environment of deposition.

Moisture content varied widely within the sampling area. Between OKOL-1 to OKEA-19, moisture contents were significantly high, generally above 80%. However, EA FW-1 to FW-9, moisture contents were lower and averaged 55%. The bulk unit weights exhibited a lower degree of scatter in comparison with the moisture content. The bulk unit weight ranged from 12.4 kN/m^3 prevalent between OKOL-1 and OKEA-19 to about 17kN/m^3 generally observed between EAFW-1 to FW9. Although density is expected to vary with water depth as shown by Tenzer and Gladkikh, (2014), this trend is not obvious at the study area (Fig.8), possibly because of the narrow water depth window considered in this study.



(a) Study area (b) After R.Tenzer and V.Gladkikh (2014)

Fig. (8) Variation of density with water depth

The sediments are generally soft to firm as indicated by vane shear strengths varying from 16 to about 50 kN/m^2 . Sediments with higher moisture content generally exhibited lower undrained vane shear strengths. The vane shear strengths measured on board and in the laboratory were generally comparable. Values of undrained cohesion recorded in the laboratory triaxial test indicated values that confirmed both on board and laboratory shear vane tests. Sediments also have some silt and fine sand content which is responsible for the low angles of internal friction exhibited. Analysis of the ultimate bearing capacities of the sediments using Terzaghi's bearing capacity formula, indicated values from 45 to 270kN/m^2, suggesting that there are sections within the study that can meaningfully support the weight of loaded pipelines on the surface of the seabed.

Whereas sediments between OKOL-1 and OKEA-6 are generally soft and weak those between OKEA6 and FW-9 are may be considered as soft to firm. This means that only part sections of the pipeline route can be readily fluidized by high pressure jetting for pipeline placement purposes. The other section would require to be cut, although the walls of the excavations that will be created are unlikely to be stable. Sediments, when super-saturated can be expected to flow when disturbed such as during excavations, in which case, pipeline route excavation and burial can be undertaken concurrently.

The particle size distribution of the sediments reveals variations across the study area (Fig.9). The shore areas comprise silty materials as against silty clay size fractions found in further offshore areas. This range of sediments can be potentially transported as suspended load by currents and waves.

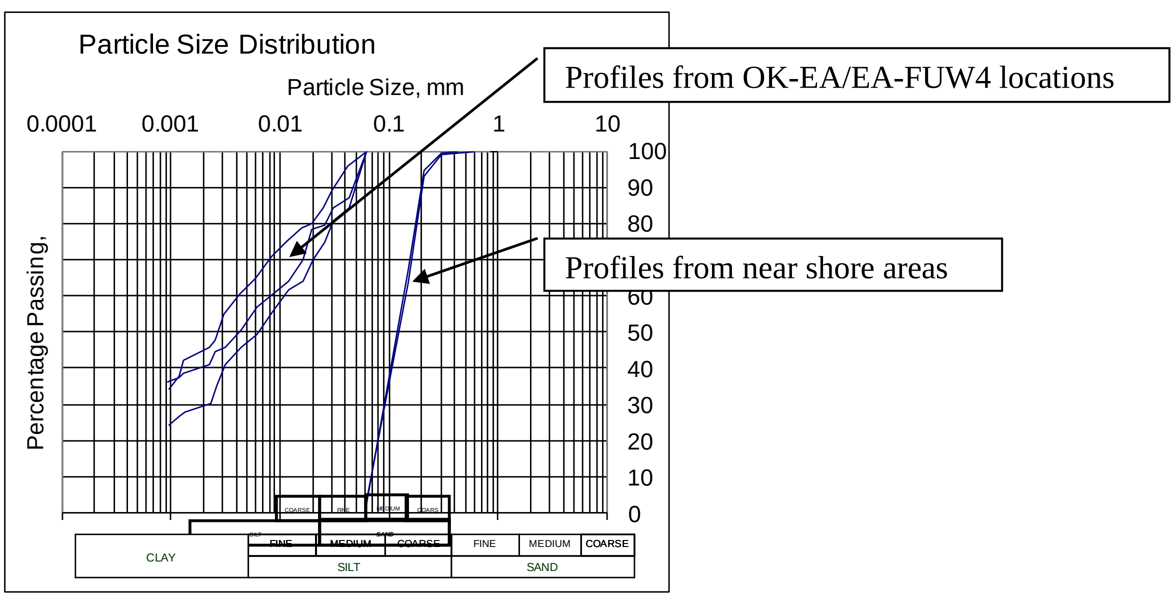


Fig. (9) Particle size distribution for shore area and deeper OK-EAS and EA-FUW4 locations

The variation of bulk density shows a gradual increase in bulk density towards the shore (Fig.10), reflecting the influence of increased granualar particle composition and depositional energy. The increase in unit weight towards and normal to the shoreline within the study area is approximately at the rate of 2.57x10^{-6} kN/m^3/km. In contrast, the moisture content increases offshore (Fig. 11) because of the increased fines content in that direction. Within the study area, the rate of increase averages 7.142x10^{-5}%/km in the offshore direction.

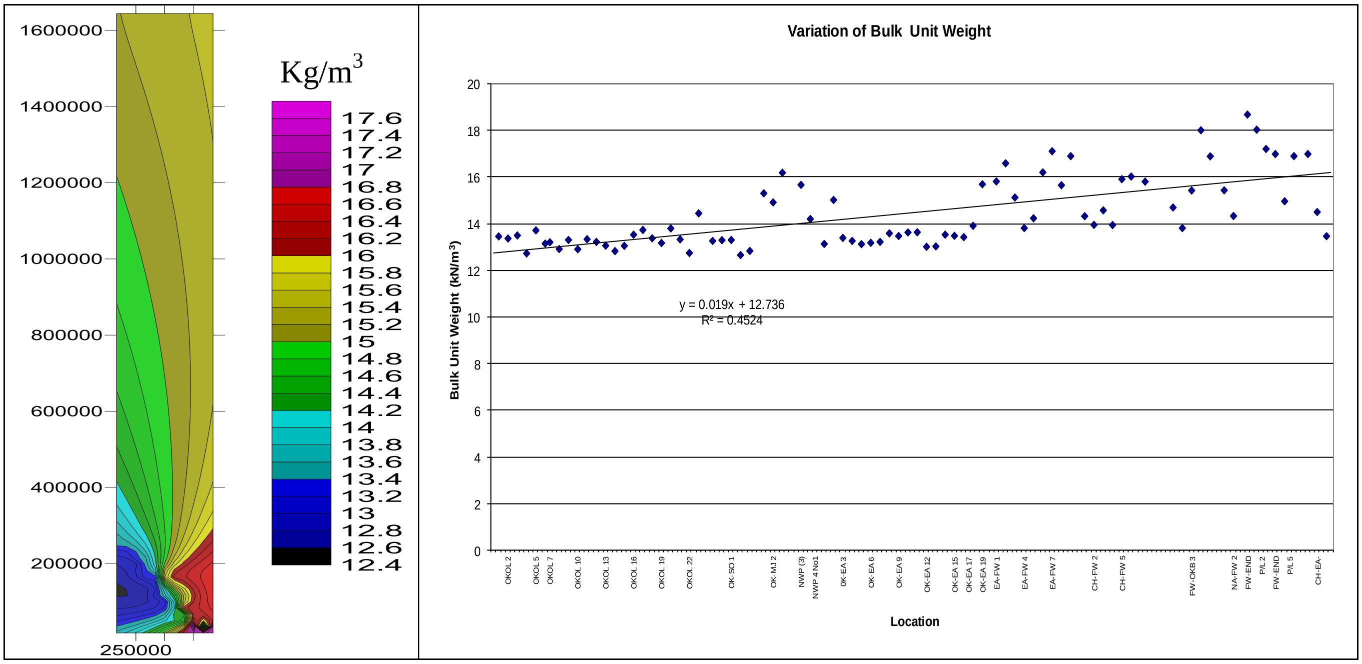


Fig (10) Spatial variation of Bulk Density across study area

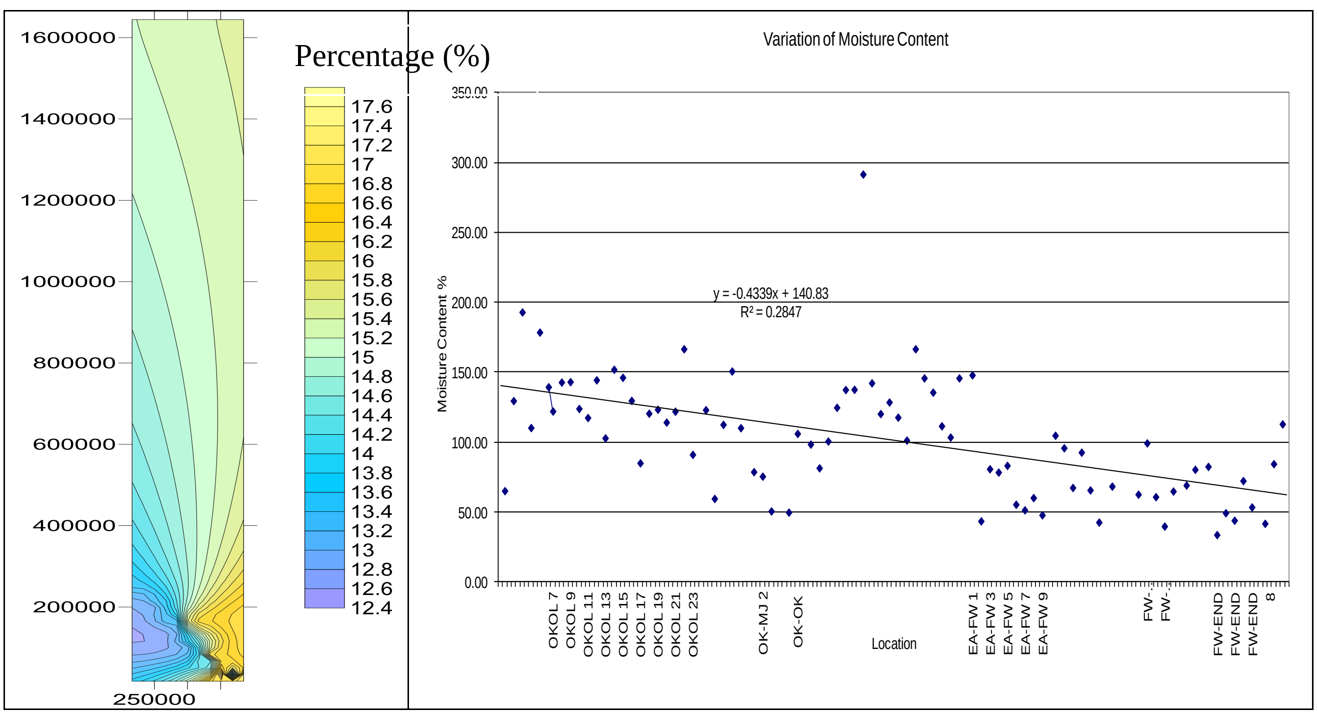


Fig (11) Spatial variation of Moisture Content

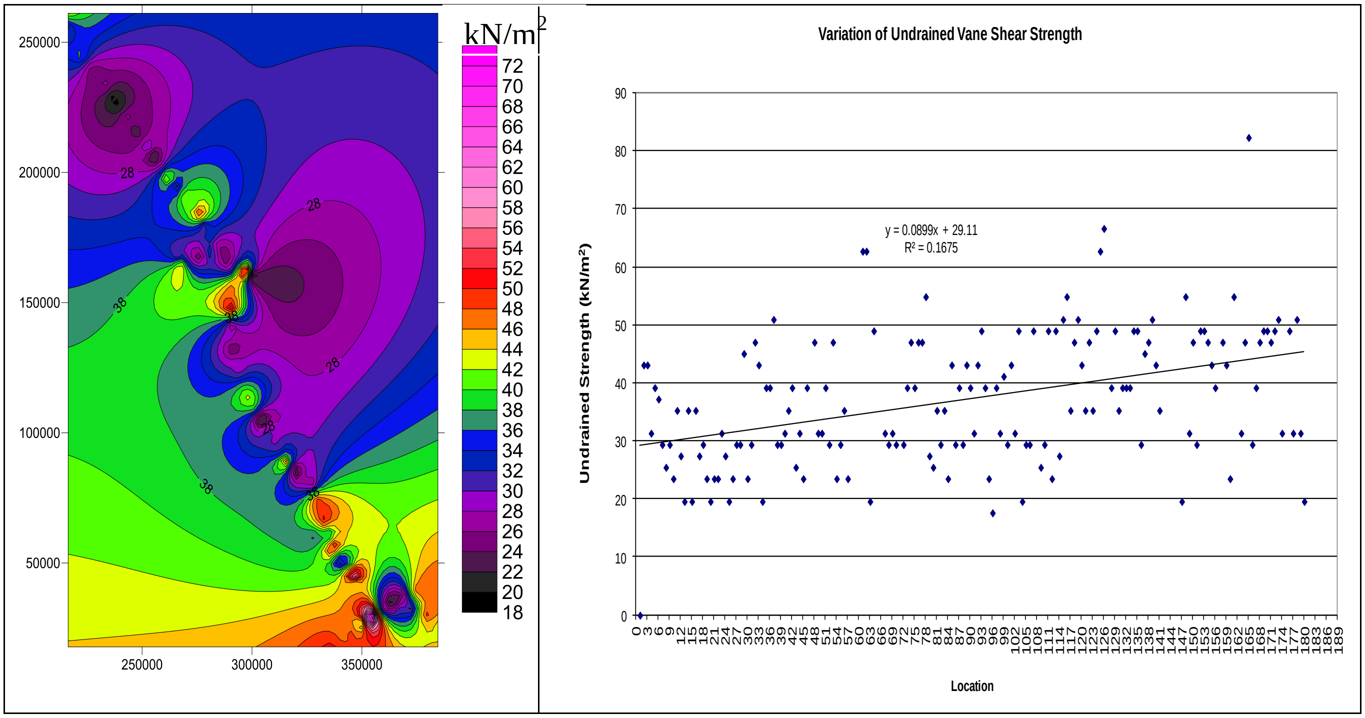


Fig (12) Spatial variation of Vane Strength

Although the undrained vane shear strength varied widely with considerable scatter (Fig. 12), it showed an underlying trend that increases towards the shore at an average rate of 1.286×10^{-5}kN/m^2/km. A plot of the Atterberg limits showed clusters in three areas (Figs. 13 to 15), indicating three possible predominant sources of fine sediment fractions. The liquid, plastic and plasticity indices of the sediments from the offshore locations showed very high values compared to the near shore. The nearshore sediments areas while being relatively lower showed considerable scatter, suggestive of possible multiple sources of fines. The sediments from the intermediate location of OK-MJ5 and EAS showed the lowest values of the Atterberg limits. The spread of data points in the plasticity chart (Fig. 16) confirms the multiple types of clay mineralogy and sources. The range in liquidity indices (Fig.17) indicated that the sediments are mostly between semi-solid and solid, in an underconsolidated state.

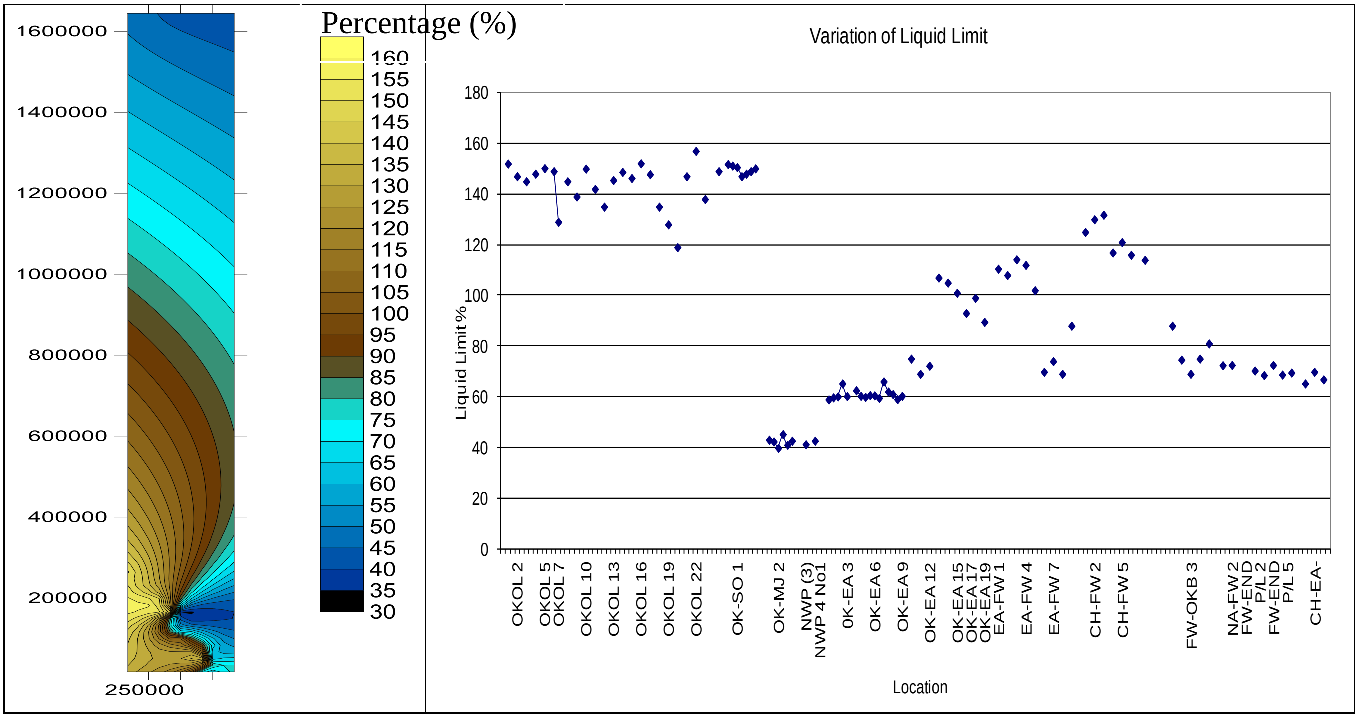


Fig (13) Spatial variation of Liquid Limit

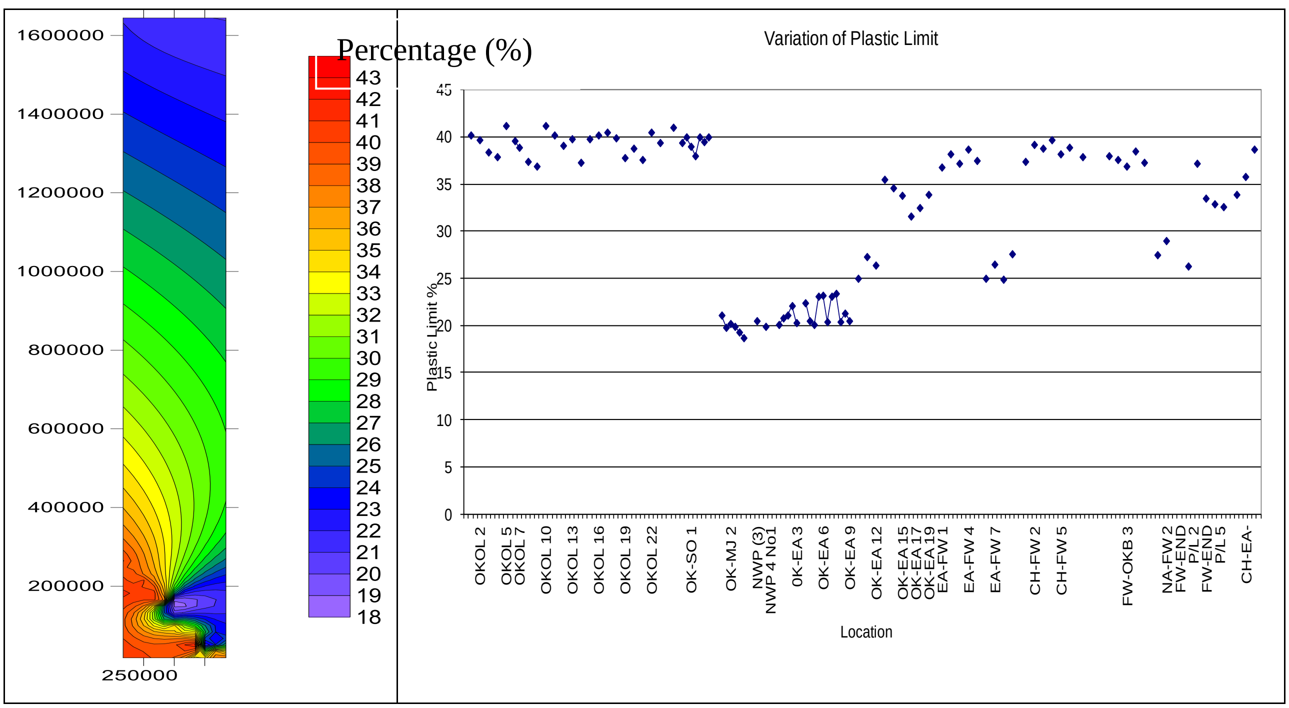


Fig (14) Spatial variation of Plastic Limit

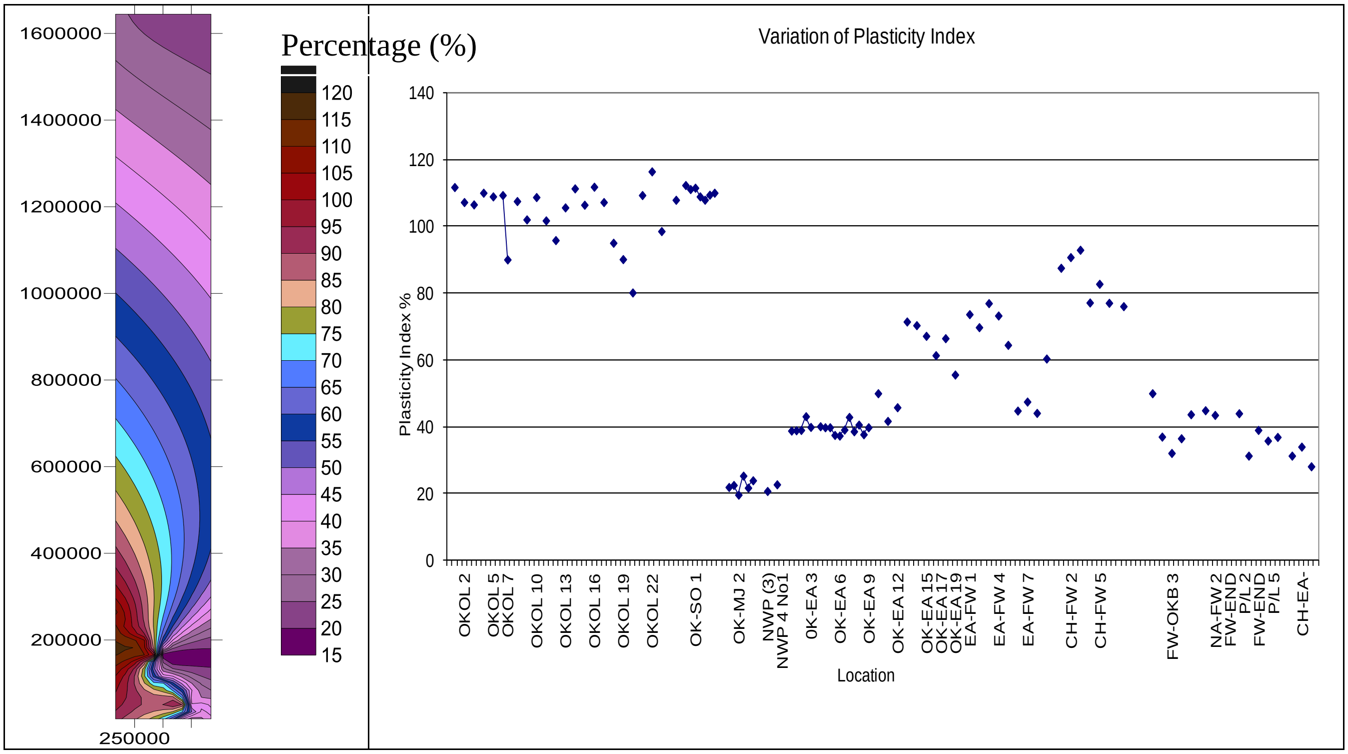


Fig (15) Spatial variation of Plasticity Index

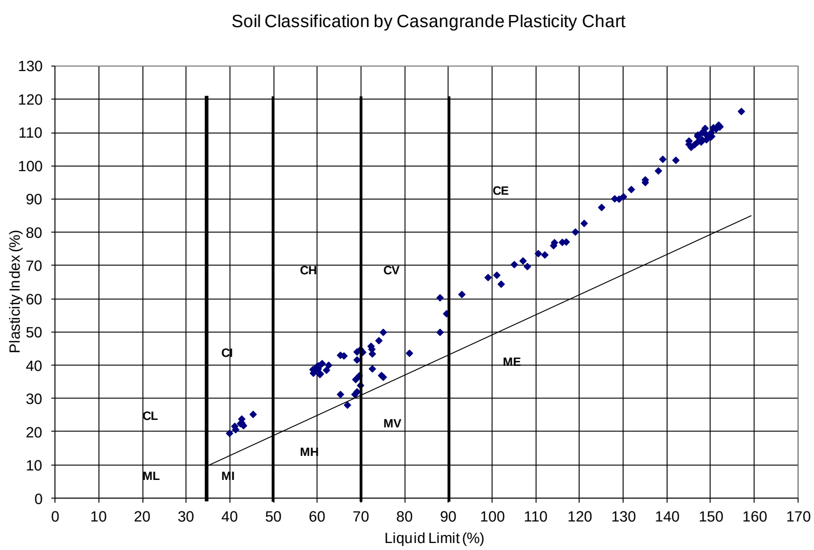


Fig. (16) Plasticity chart

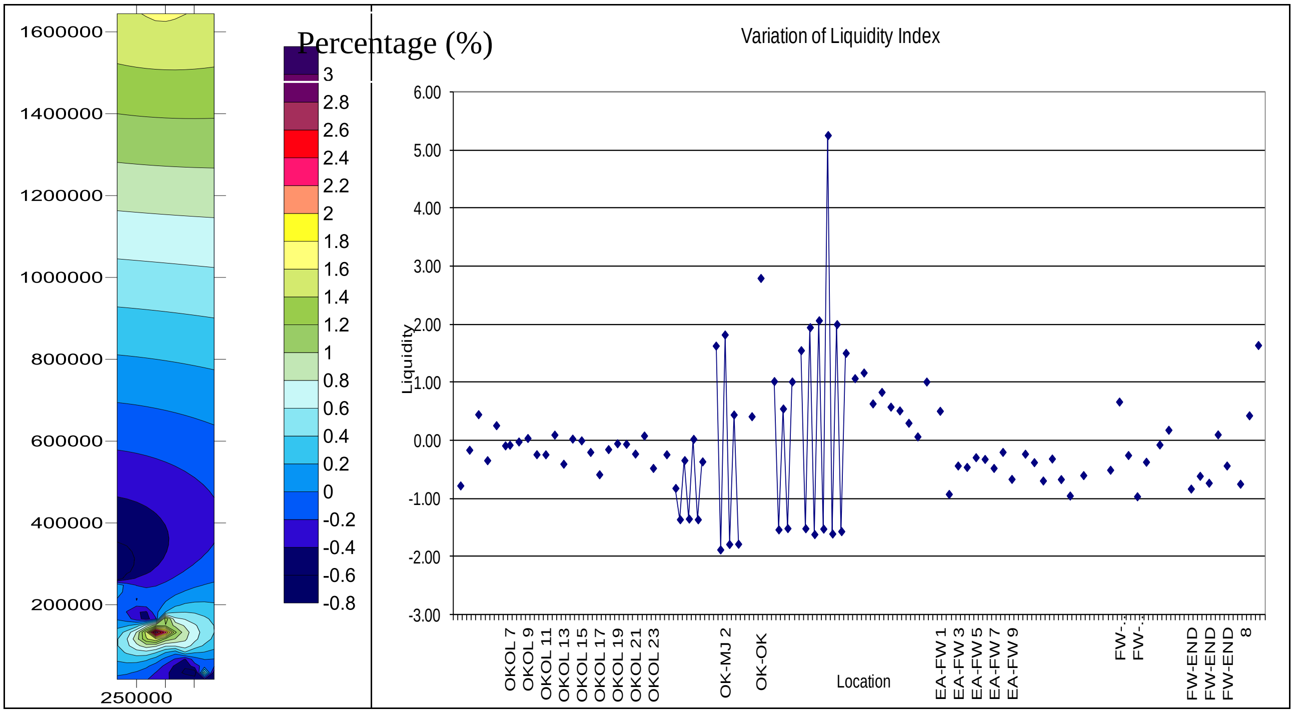


Fig (17) Spatial variation of Liquidity Index

The electrical conductivity (Fig.18) of the sediments decreases onshore at a rate of $7.14x10^{-3}$µs/cm/km. This is possibly because of the role of fresh water discharges into the ocean from the various river estuaries in the region. It is estimated that $1x10^{12}$ m3/yr of fresh water flows through the western half of Nigeria into the Atlantic Ocean (Rider 2004). Both organic carbon (Fig.19) and organic matter concentration in the sediments show similar trends of decreasing concentration towards the shoreline in much the same fashion as the moisture content and particle size distribution. Whereas organic carbon decreases at the rate of $1.071x10^{-6}$%/km, Organic matter decreases at the rate of $1.5x10^{-6}$ %/km towards the shoreline.

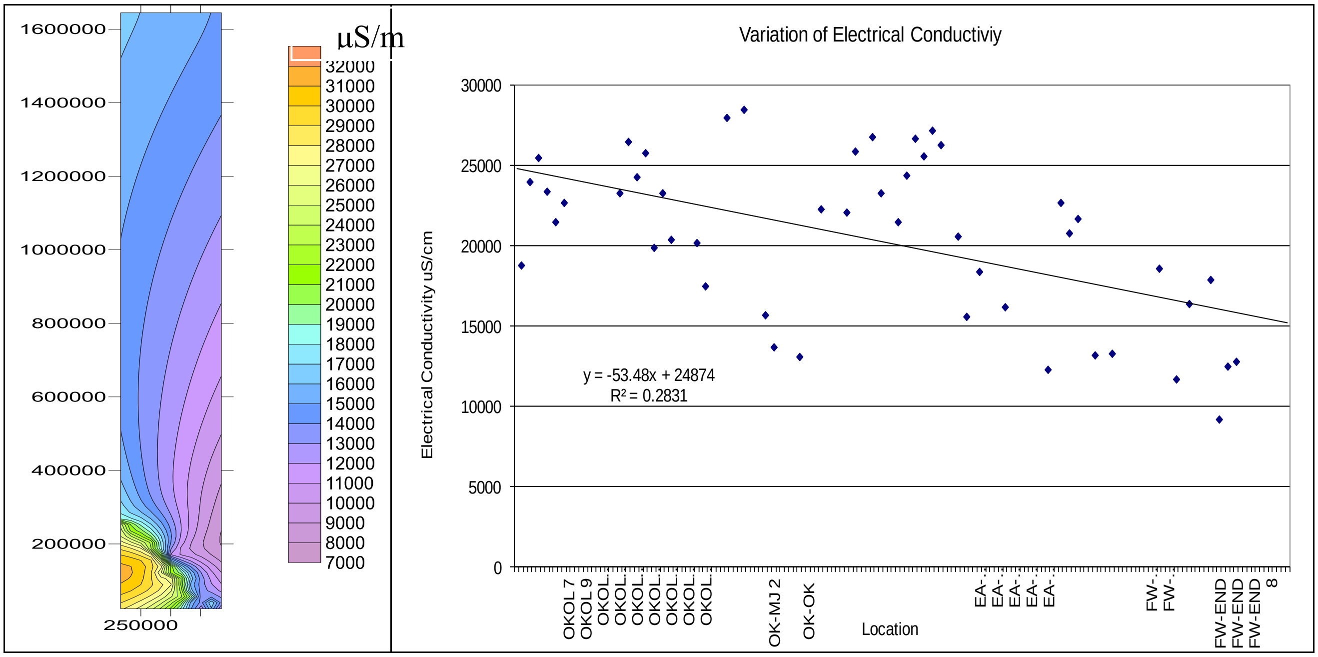


Fig (18) Spatial variation of Electrical Conductivity

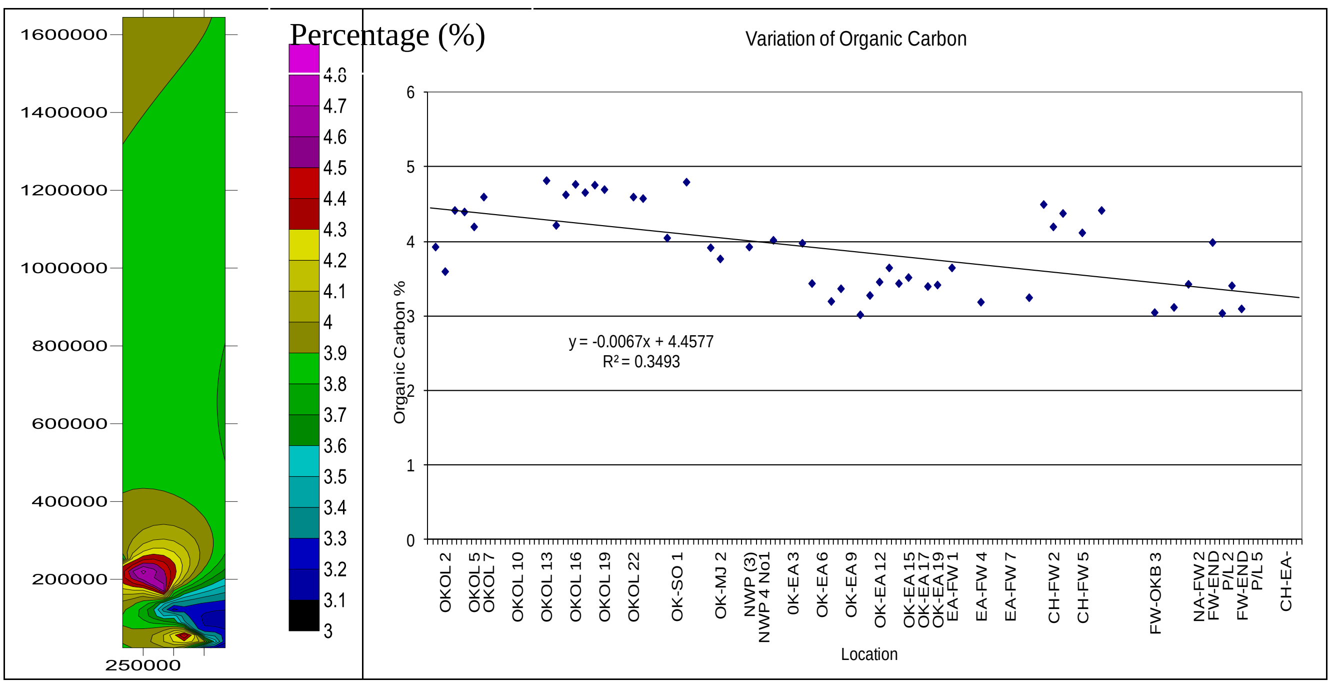


Fig (19) Spatial variation of Organic Carbon

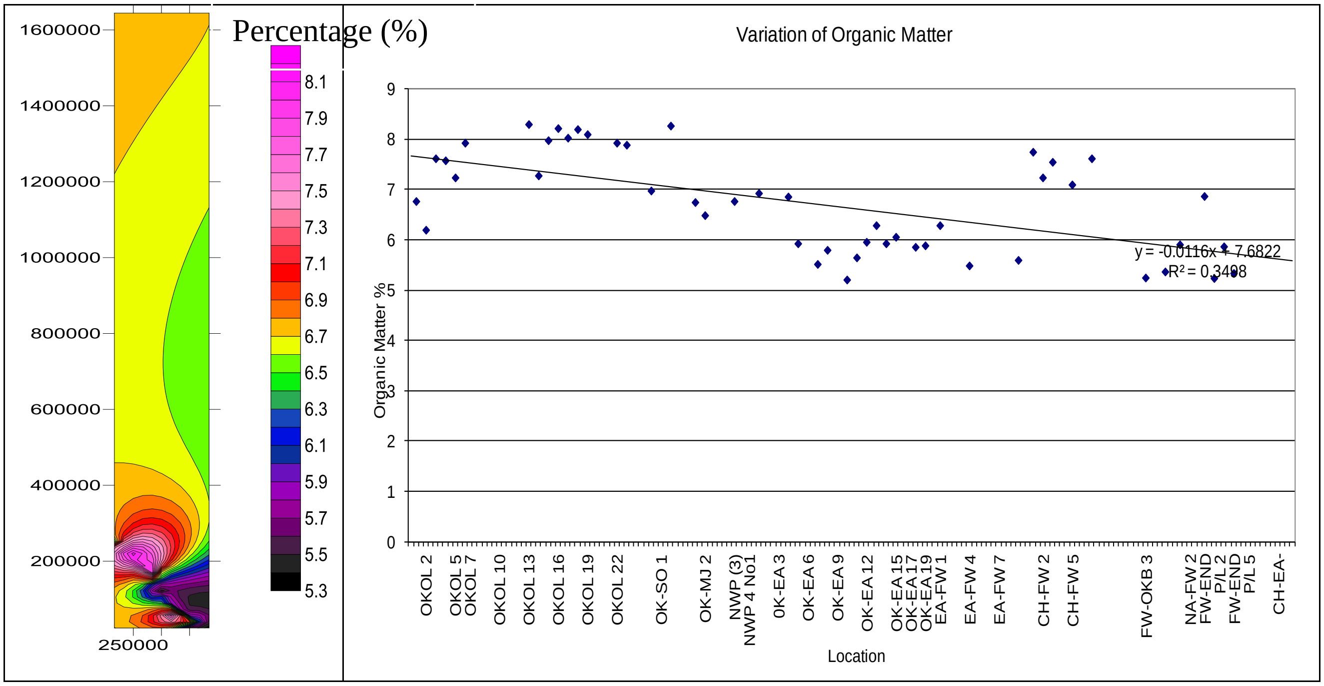


Fig (20) Spatial variation of Organic Matter

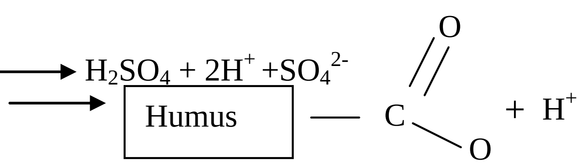
Physicochemical characteristics of sediment

Physicochemical characteristics of sediment samples collected from the seabed around the study area indicate that the pH was mildly alkaline in reaction and ranged from 7.4 around OKOL to 8.0 in the area of CH – FW which are fairly uniform, due probably to the equal balance of the acid and the alkaline components in the study area. The electrical conductivity values are moderate high (9200 – 28500 μS/cm) indicating accumulating of large deposits of salts. Organic matter contents varied between 5.25% (FW – OK) and 8.30% (OKOL). These sediments when exposed the organic matter will undergo oxidation processes releasing hydrogen ions (H^+) from the carboxylic (-COOH) and phenolic (- OH) groups

Organic matter + O_2

Thus, resulting in the sediment acidity (Biswas and Mukherjee, 1994; Isirimah *et al* 2003). Sulphate concentrations ranged from 19.22ppm at FW – OK to 30.21ppm around OK – SONAM 2. The amount obtained indicate that there are acid – sulphate salts which are responsible for the acidification of the environment due to the production of the free acid substances such as sulphuric acid, when the sediments are exposed (Isirimah et al, 2003).

$$2S + 3O_2 + 2H_2O \longrightarrow H_2SO_4 + 2H^+ + SO_4^{2-}$$



Thus, organic matter and sulphur compounds oxidation may produce sediment acidity that will that will cause in corrosion of materials in the system. The concentration of the carbonates which ranged from 2.11% around FW – END P/C to 3.09% around OKOL indicates that there are large quantities of basic salts, mainly carbonates of calcium and sodium. This indicates that there will be deposition of scales on the surfaces of materials in the environment in wet conditions. On the whole, the physicochemical characteristics of the sediments investigated revealed that there are large accumulations of salts comprising both acid and alkaline properties in reaction with alkaline salts dominating in the environment; this might lead to deposition of scales. But on exposure to the atmosphere, organic matter and sulphur compound will oxidize to increase the acid components and enhance corrosive actions in the sediment.

5 Conclusion

Based on the systhesis of data, this study concludes that several of the geotechnical parameters vary systematically along a traverse perpendicular to the shoreline suggesting the overwhelming influence of trend vectors such as waves, tides and wind in the distribution of sediments within the continental shelf. The wide range of plots of sediment plasticity is an indication of the multiple sources of fine sediments transported to the shelf.

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