Geotechnical characteristics of a selected shallow marine area considered for quay wall construction

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Abstract. Quay wall defense systems are useful marine structures for berthing of vessels and other marine operations. Before quay-walls are constructed in shallow marine areas, there is need for adequate subsurface investigation to ensure proper design and construction of quay-walls that will be able to satisfactorily support the facilities they are intended for. This research work focuses on subsurface investigation involving the geotechnical characterization of soil in a selected shallow marine area in the Niger Delta area of Nigeria. Percussion rigs were used for both the on-land and over-the-water borings. A total of seven (7) on-land and six (6) over-the-water borings, all to a depth of 40 m each below existing ground level and sea bed respectively, were carried out. Field and laboratory tests were performed in order to effectively characterize the soils. Stratigraphy of on-land borings showed soft fibrous organic peaty clay layer, underlain below by silty sands and clays. Beneath this layer to the end of boring is well-graded sands and gravels. The borings over-water had a very soft to soft clay layer underlain by silty sands, being underlain by poorly-graded sands and well-graded sands to the limits of the borings. Deep foundation systems employing reinforced concrete piles to depths (coinciding with the sandy horizon) were recommended for the on-land piles, reinforced hollow cylindrical steel piles for piers and piles for offshore landing jetties, and concrete sheet piles for shore protection works. This will form the ballasts for mooring of cargo vessels for conveying oil and gas final products.

1. Introduction

Shallow water marine environment refers to areas between the shore and deeper water, such as a reef wall or a shelf break [1]. This environment is characterized by oceanic, geological and biological conditions. The water in this environment is shallow and clear, depending on seasonal changes, allowing formation of different sedimentary structures, carbonate rocks, coral reefs, and allowing certain organisms to survive and become fossils [1].

Similarly, quay walls are referred to as earth/water retaining structures which are used to dock floating vessels and transfer goods [2]. Quay walls are of various types and are used for mooring and berthing floating vessels such as barges, container vessels, ship and boats [2]. Quay walls are one of the most essential components of port infrastructure and with growing volumes of cargo and increasing vessel sizes, the demand on these structures is increasing [2]. Efficient transfer at the quay wall interface is required for the commercial and operational success of any terminal or port [2].

Considering the case study area, Port Harcourt Port is a multi-purpose port and plays the centre-point role to other jetties around that locality through the provision of guidance, navigations and other towage
services, by providing serviced for various markets relating to liquid, dry and general cargo trades [3]. One of these jetties is the Shorelink Oil and Gas jetty being investigated, located at Rumuolumeni in Port Harcourt Rivers State [4].

Various activities around the coastal areas and along the shore as found in ports, wharfs, dockyards, etc., and the frequent failures of facilities experienced in recent times, necessitates the need for adequate knowledge about the underlying soils that supports these marine facilities, to prevent avoidable failures like retention wall buckling, overturning, sliding, foundation failures etc, as seen on coastal facilities across the Nation [5]. Some of the failures experienced in the past are shown in Figure 1.

![Figure 1. CMS-Jetty Marina-Lagos and Naval Base Lagos.](image-url)

In Nigeria, commercial activities in the coastal areas is pronounced in areas like Lagos, Warri and Port Harcourt, hence, this study will focus on cases in Port Harcourt and probably Lagos marine environment. Based on previous studies and projects, there exists peculiar soil conditions around and along the shores where facilities like quay walls at ports, dockyards and wharfs are situated. Knowledge of these ground conditions will guide designers in their studies and design prior to detailed investigations and surveys that will help provide on-hand information for design and economic planning. Good familiarity with the soil conditions, types, properties and occurrence will aid proper quay wall and other marine infrastructures design and construction that will adequately support any development proposed in the marine environment. Consequences of these failures result in loss of lives, time and properties.

Detail geotechnical investigations and laboratory tests and analysis were performed at locations considered for this study at different times as would be discussed in the subsequent sections. These surveys and tests were used to determine conditions, properties and characteristic of soil below these location, for the purpose of designing appropriate foundation/shoring systems for quay walls [6,7].

Field survey employed involve boring, sounding and soil samplings. Thirteen (13) borings comprising of 7 No. points (On-Land) and 6 No. points (Over-Water) were probed down to the final depths of 40.00-meters based on past experience and knowledge of the project site. The borings employed a Shell-and-Auger Rig. Standard Penetration Tests (SPT) was carried out at depth intervals of 1.50 meters in all boreholes or where a change in soil lithology was observed during the boring process. Altogether, a total of 96 SPT soundings were carried out (from the 13 sampling Boreholes). Both undisturbed samples, with Split Spoon Samplers and U-4 tubes, and slightly disturbed soil samples using Shelling Augers, were obtained during the boring process. Field and laboratory visual examinations as well as detailed laboratory testing were performed on the retrieved soil samples [7].
The purpose of the investigation is to provide a combined geologic and geotechnical engineering investigation useful for sound engineering design of foundation systems for the quay wall [8].

With the rate of development along the coastal axis of the country, springing various construction of marine infrastructures, adequate attention, earlier denied, has to been given to deposits in the coastal regions of Nigeria, especially the coastal regions where commercial operations are eminent. Therefore, to the authors’ knowledge, deposits underlying the coastal region in Nigeria have not received sufficient attention, and the advantages to the nation’s economy have not been optimized. This study provides general geotechnical information of the Port-Harcourt marine soil formation as basis for future development of sustainable quay wall construction and other infrastructures in the area. The knowledge of the soil properties will enable the understanding of the general behavior of coastal soils in the region for recommendation, design and construction of foundations that will be suitable for coastal structures [7].

2. Materials and Method

2.1. Materials
The geotechnical investigations and all the test facilities were provided by TEKS Geotechnical Consultancy Nigeria Limited based in Port Harcourt Nigeria. TEKS Company was the geotechnical contractor, commissioned by Shorelink Oil & Gas Services Limited, of the case history in the study area of Rumuolumeni-Port Harcourt in Nigeria [4].

2.2. Study Case
The project site is located at Shorelink Oil & Gas Company Rumuolumeni, Rivers State. Geographically, the project site is delimited by Latitudes 04°47'43.2" and 04°47'49.5" North of the Equator and Longitudes 006°55'35.9" and 006°56'35.9" East of the Greenwich Meridian. The satellite imagery shown in Figure 2 shows the Shorelink Oil & Gas Company Project Site and the test point locations [4].

![Figure 2. Location map of Shorelink Oil & Gas Company Project Site (Testing and Sampling Site).](image)

The area investigated falls within the Tertiary Niger Delta which occurs at the southern end of Nigeria bordering the Atlantic Ocean and extends from about longitude 30-90E and latitude 40 30’ - 50 20’N.
2.3. Methods

Collection of Soil samples: The Subsurface conditions at the project site were studied by sounding in the form of Standard Penetration Testing (SPT) and boring holes with the aid of Shell and Auger Percussion Rig (Figure 3) while retrieving soil samples at specific depth intervals of 1.50 meters (on-land) and 1.00 meter (over-water) for laboratory tests purpose. The Bearing Capacities of the various soil layers at the site were determined using the SPT Test data. These methods gave valuable information about the subsurface characteristics at the project area. In general, disturbed samples were obtained during the investigation with Shell-and-Augur equipment. Undisturbed samples were recovered from the cohesive layers by driving a 100mm-diameter sampler through a total distance of 450mm. These samples were taken at relevant depths. All depths are in relation to the existing ground level at the time of investigations [3,7].

![Figure 3. Photographs showing subsurface exploration process (onshore and offshore) during field work.](image)

Table 1. Locations of Borehole (On-Land).

| Boring No. | Elevation Above Sea Level (m) | GPS Locations Northing | GPS Locations Easting | Water Table Depth (m) | Remarks |
|------------|-------------------------------|-----------------------|----------------------|----------------------|---------|
| BH-1       | 3.0                           | N04° 47’ 48.7”        | E006° 56’ 18.0”      | 0.00                 | Elevations are approximated to the error levels of the GPS equipment |
| BH-2       | 3.0                           | N04° 47’ 48.7”        | E006° 56’ 18.0”      | 0.00                 |         |
| BH-6       | 7.0                           | N04° 47’ 49.5”        | E006° 56’ 18.0”      | 0.00                 |         |
| BH-8       | 3.7                           | N04° 47’ 48.1”        | E006° 55’ 59.1”      | 0.00                 |         |
| BH-10      | 4.7                           | N04° 47’ 45.9”        | E006° 55’ 51.9”      | 0.00                 |         |
| BH-12      | 3.8                           | N04° 47’ 43.2”        | E006° 55’ 41.9”      | 0.00                 |         |
| BH-14      | 2.0                           | N04° 47’ 45.3”        | E006° 55’ 35.9”      | 0.00                 |         |

A total of thirteen (13) borings were made to a depth of forty (40) meters (each) at the project site [4]. The first seven (7) boreholes (BH-1, BH-2, BH-6, BH-8, BH-10, BH-12 and BH-14) were located on-land along the shoreline at about 15.0/20.0m to the shoreline of the river while the other six (6) geotechnical
boreholes (BH-3, BH-5, BH-7, BH-9, BH-11 and BH-13) were probed at about 10.0/15.0m over water away from the shoreline as shown in Table 2.

Table 2. Locations of Borehole (Over-Water).

| Boring No. | Elevation Above Sea Level (m) | GPS Locations | Water Table Depth (m) | Remarks |
|------------|------------------------------|---------------|-----------------------|---------|
| BH-3       | -2.1                         | N04° 47' 47.1" E006° 56' 13.0" | 7.0 7.5 | Elevations are approximated to the error levels of the GPS equipment |
| BH-4&5     | -2.1                         | N04° 47' 47.3" E006° 56' 9.10" | 4.0 4.5 |
| BH-7       | -2.1                         | N04° 47' 46.30" E006° 56' 3.10" | 7.5 7.5 |
| BH-9       | -2.1                         | N04° 47' 44.9" E006° 55' 55.4" | 4.5 4.5 |
| BH-11&13   | -2.1                         | N04° 47' 42.2" E006° 55' 44.7" | 4.5 4.5 |
| BH-15      | -2.1                         | N04° 47' 41.6" E006° 55' 37.4" | 4.5 4.5 |

Standard Penetration Tests (SPTs) were carried out in cohesion-less strata at depths interval of 1.5 meters. The number of blows required to drive the split spoon sampler through a distance of 300mm, after the initial penetration of 150mm, was recorded as the $N_{SPT}$ value [9,10]. The retrieved soil samples from the boreholes (onshore and offshore) were packed and labelled properly, and transported properly to the laboratory for testing.

Experimental Programme: Various tests performed at the laboratory on selected soil samples from the site borings are Visual Classification of soil samples, Grain Size Analysis, Consistency Limits (Atterberg Limits), Unit Weights determinations, Unconsolidated-Undrained Tri-axial Tests and Oedometer Consolidation Tests [4,7].

These tests were carried out to determine the soil engineering properties and strength characteristics for the purpose of designing a robust foundation and shore protection walls at the project site [9,10]. All the tests were performed in accordance with the British Standards (BS 1377, 1990; Methods of test for soils for civil engineering purposes).

3. Results and Discussion
3.1. Visual Classification of Soil Samples
Basically, the subsurface soils materials at the project sites are: an upper Soft light-dark brown/reddish brown organic Sandy Clay/Clayey Sand Layer (SC) which is underlain by loose reddish-brown to white Poorly-graded sand Layer (SP) [4]. These are further underlain by loose brown to white well-graded sand layers (SW) [4].

The above soil types characterize the project site down to depths of 40.00 m. The lithology of the soils underlying this site is shown in Figure 4, for the test point carried out on land while Figure 5 presents the soil profile of borings performed over water.
Figure 4. Fence Diagram of Lithologs representing borings drilled at the project site (on-shore).

Figure 5. Fence diagram of lithologs representing borings drilled at the project site (off-shore).
From the field and laboratory investigations carried out on the subsurface materials from the site, it is observed that basically about seven (7) identifiable soil profiles exist along the stretch of the 1.4km Quay Wall line investigated [4]. These are:

- Dark Greyish Organic CLAY (OH)
- Reddish Brown Clayey SILT (ML)
- Dark Greeyish Sandy CLAY (SC)
- Milkish Silty SAND (SM)
- Brownish/Greyish Silty Gravely SAND (GM)
- Milkish Poorly-graded SAND (SP)
- Milkish well-graded SAND (SW)

The following presents the various geotechnical engineering properties of each of the sub-soils [4].

### 3.2. Grain Size Analysis:
Grain size analysis involved both dry sieving and wet hydrometer analyses on the field obtained samples [4]. Grain size pattern for BH-3 is presented in Table 3 and the particle size distribution chart is shown in Figure 6.

**Table 3. Grain Size Distribution Patterns for BH-03.**

| Soil Type                              | % Passing Sieve Sizes |
|----------------------------------------|-----------------------|
|                                        | >4.75 mm  | 4.75 mm  | 75 μ     | 2 μ      |
| Dark grayish Organic CLAY Layer (OH)   | 20-34      | 12-14    | 7-10     | 0-2      |
| Dark Poorly Graded SAND Layer (SP)     | 20-28      | 10-14    | 6-9      | 2-5      |
| Dark grayish Clayey Silt Layer         | 22-24      | 11-12    | 6-8      | 2-3      |
| Light brownish Well graded SAND Layer  | 16-28      | 4-14     | 0-8      | 0-5      |
| Light brownish Silty SAND Layer (SM)   | 12-15      | 10-14    | 6-9      | 0-5      |

**Figure 6.** Particle Size Distribution for soils from BH-3, at Depths: 15 m, 19.5 m, 29 m, 33 m & 36 m.
3.3. Consistency Limits: Atterberg limits was evaluated on the soil samples, comprising of liquid limits, plastic limits and hence plasticity indices. Natural moisture contents and Liquidity Indices of the soil samples were also measured [4,7].

- Liquid Limit: The Sandy Clay/Clayey Sands Layer (SC) materials are cohesive and possess Liquid Limit (LL) of 15.1 to 20.6. The Poorly-graded Sands and Well-graded Sands (SW) Layers are Non Plastic (NP) in consistency.
- The plasticity index (PI), varies from a low of zero (non-plastic) for both the poorly-graded sands (SP) and well-graded sands (SW) to 2.60 – 4.40% for the Sandy Clay/Clayey Sands Layer (SC).
- The natural moisture contents of the soil samples were determined in accordance with recommended standards and expressed as percentages of oven-dry weights of soils. The Sandy Clay/Clayey Sands Layer (SC) materials have moisture contents of 10.8 to 18.45%, while the Poorly graded Sands (SP) beneath have moisture contents of 4.0 to 6.0%. The Well-graded Sand and Gravels (SW) have natural moisture contents of 4.0 to 6.0 % also.

3.4. Unit Weights: Unit weights of the soil materials in each subsurface soil at the site were determined. The saturated unit weights ($\gamma_{sat}$) of the Soft Sandy Clay/Clayey Sand Layer (SC) materials were found to be 17.8 - 20.8 kN/m$^3$ while those of the loose Poorly-graded Sands Layer (SP) beneath were found to be 23.8 - 24.8 kN/m$^3$. The Loose to medium dense Well-graded Sands (SW) had unit weights ranging between 23.8 - 25.2 kN/m$^3$ [4].

3.5. Unconfined – Undrained Triaxial Tests: Unconsolidated-Undrained (U-U) Triaxial Test was utilize to evaluate the shear strength of soils underlying the project site. Similarly, the strength properties of the subsurface soil were measured by means of the Undrained-Unconsolidated (UU) triaxial compression tests [4].

In the Undrained-Unconsolidated Triaxial Tests, values of both undrained cohesion ($C_u$) and undrained friction angle ($\phi_u$) were obtained as indices of strength of the c- $\phi$ materials at the site. Each specimen of 35mm diameter and 110mm height was prepared from slightly disturbed samples obtained with U-4 Shelby tubes of 120mm diameter and tested in unconsolidated-undrained (U-U) compression using cell pressures of 50.0, 100.0 and 200.0 kPa, respectively [4].

Soil Bearing Capacity: Terzaghi One- Dimensional Oedometer Consolidation Test was employed to calculate the bearing capacity values of the subsurface materials at the project site. The parameters obtained and determined during the consolidation tests are:

The coefficient of volume compressibility ($M_v$): $M_v$ parameter determines the area that is likely to be compressible when subjected to a given amount of load; and the coefficient of consolidation ($C_v$), indicating the likely rate of settlement per annum under the given loading conditions.

Pressure range of between 50.00 and 400.00 kPa was used for the one-dimensional Oedometer Consolidation Tests on cohesive soil samples.

Coefficient of Volume Compressibility ($M_v$): The oedometer tests carried out on some soil samples indicate that the Coefficient of Volume Compressibility ($M_v$) for the top Soft Sandy Clay/Clayey Sands (SC) under confining pressures varying from 50.00 to 400.00 kPa, was between 0.14 m$^2$/MN x 10$^{-4}$ and 0.28 m$^2$/MN x 10$^{-4}$ respectively.

Coefficient of Consolidation ($C_v$): Oedometer tests performed on some soil samples, that is Soft Sandy Clay/Clayey Sands (SC)) from the borings reveal that the Coefficient of Consolidation ($C_v$) was about 0.45 m$^2$/yr – 0.78 m$^2$/yr under an overburden pressure of 50 kPa, while it was about 0.24 – 0.58m$^2$/year under an overburden pressure of 400 kPa, for the overlying.
3.6. Foundation Type Options Recommended: Based on the types of subsurface soil encountered at this site, outcomes of the geotechnical and laboratory analyses, only Deep walls should be adopted for shore protection works in this area. In using deep shore defence walls, Concrete Sheet Pile Walls adequately anchored behind, for stability against horizontal forces anticipated at the site, are therefore most preferred (Figure 7) [4]. The type of piles recommended is Pre-cast Reinforced Concrete Sheet Piles because of their durability in saline water and their ease of installation at site with appropriate installation methods [10]. Table 4 presents the safe bearing capacities obtained from each borehole at various depths, between 25.0m and 40.0 m below existing ground/river bed levels.

![Figure 7. Proposed use of Ground Anchors at Quay Wall Shore Protection Structure.](image)

Drainage Conditions: Generally, ground water level was encountered almost at the ground surface as the area is being submerged at high tide. Values of Coefficients of Permeability (k) varies from 1.75 x 10^-6 m/sec. to 5.5 x 10^-2 m/sec. The Well-graded Sands and Gravels Layer (SW-SP) beneath are highly permeable with k values varying between 4.5 x 10^-3 and 5.5 x 10^2 [4,7].

The bearing capacities obtained for pile section was plotted against depths for BH-03, as shown in Figure 8, also correlated for all the borings on land presented in Figure 9, and for the boreholes performed over water shown in Figure 10.
Table 4. Summary of total safe loads on piles of different lengths at the various on/off-shore locations.

| BH No. | Location   | Total Pile Load (MN) | Pile Length (m) | Remarks                                      |
|--------|------------|----------------------|-----------------|----------------------------------------------|
|        |            | 25m | 30m | 35m | 40m                          |                                           |
| 01     | On-Shore   | 82.36 | 110.09 | 141.97 | 178.08 | Total pile Load based on individual Pile Length |
| 02     | On-Shore   | 83.95 | 111.46 | 143.15 | 179.02 | Total pile Load based on individual Pile Length |
| 03     | Off-Shore  | 98.47 | 127.58 | 160.27 | 196.56 | Total pile Load based on individual Pile Length |
| 04/05  | Off-Shore  | 89.82 | 227.45 | 279.32 | 922.03 | Total pile Load based on individual Pile Length |
| 06     | On-Shore   | 218.85 | 291.61 | 553.04 | 909.30 | Total pile Load based on individual Pile Length |
| 07     | Off-Shore  | 287.36 | 366.13 | 670.92 | 1221.60| Total pile Load based on individual Pile Length |
| 08     | On-Shore   | 252.03 | 317.16 | 388.18 | 1330.84| Total pile Load based on individual Pile Length |
| 09     | Off-Shore  | 281.60 | 478.22 | 707.22 | 1739.60| Total pile Load based on individual Pile Length |
| 10     | On-Shore   | 353.36 | 536.36 | 769.48 | 1353.45| Total pile Load based on individual Pile Length |
| 11     | Off-Shore  | 291.93 | 430.38 | 798.37 | 1909.97| Total pile Load based on individual Pile Length |
| 12     | On-Shore   | 118.95 | 226.98 | 342.97 | 831.63 | Total pile Load based on individual Pile Length |
| 13     | Off-Shore  | 215.40 | 517.60 | 754.97 | 1739.68| Total pile Load based on individual Pile Length |
| 14     | On-Shore   | 80.38 | 115.17 | 157.33 | 1375.00| Total pile Load based on individual Pile Length |

Figure 8. Total Pile Load versus Depth of Emplacement of Reinforced Concrete Pile along Quay Wall.
Figure 9. Plot of Pile Safe Loads versus Depths (m) for the 7Nos of Borehole on Land (On-Shore).

Figure 10. Plot of Pile Safe Loads versus Depths (m) for the 6No of Boreholes on Water (Off-Shore).
4. Conclusion
Massive mud and very soft organic soils are found to be the major superficial deposits of shallow marines [5]. The various types of quay walls that may be adopted for the shore protection in the shallow marine environments are Sheet piled quay walls, Combi walls, Steel cellular / caisson quay walls, Reinforced concrete diaphragm quay walls, Gravity block quay walls and Reinforced concrete counterfort quay walls [2]. Choice of wall would depend on several factors like the type of load combination, condition of the overburden layers, marine environmental condition, etc.

In making these comments, emphasis has also been placed on comparative profiles of soil and values of bearing pressures obtained in similar soil conditions elsewhere within shores of Lagos and the Niger Delta sub-region and adjoining flanks [7]. Also from the past investigations by some contractors (Trevi Foundations-Lagos in 2013 and Geoscan Engineering-Lagos in 2012), it was revealed from the subsoil investigation results that the superficial top layer along the shore lines and at shallow marines are saturated organic clay. Except for the reclaimed filled areas which has consolidated over years to loose sand layer which is also underlain by a highly compressible saturated clay layer, which exhibits poor mechanical and engineering properties from the various field investigation. This is also followed by loose to medium dense, fine to coarse-grained sand to depths varying between 30 to 40 m below ground/water level.

This study has therefore shown that the soil along the shallow marine areas is underlain predominantly by a highly compressible very soft to soft organic clay, being followed underneath by fine to coarse grained medium to very dense sands, poorly graded at the top, implying relatively high permeability potential, but improving with depths. The bearing capacities computed for pile section revealed a very low pressures at shallow levels which drastically improved as depth advances as shown in Figure 9 and Figure 10. In view of the superficial loose sand and compressible organic clay, adequate embedment, into the medium dense to very dense sand from 20.0 m down (as discussed in the previous section), should be considered for a safe shore defense wall proposed along shallow marines of the investigated areas.

Results of this study therefore constitutes useful preliminary information required for future planning and shore defense development in the marine environments in Nigeria.

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