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Stratigraphic Constraints to Shallow Foundation Design in the Coastal Zone of Nigeria

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Abstract

The coastal zone of Nigeria comprises the Beach ridges and mangrove swamps. The zone is underlain by an alternating sequence of sand and clay with a high frequency of occurrence of clay within 10m below the ground surface. The proximal location of compressible clays to the surface increases the influence of imposed loads, with the consequence of consolidation settlement. The impact of imposed load is exacerbated by the thickness and consistency of the compressible layer. A chart based on dimensionless coefficients to facilitate the design of shallow foundation in environments typified by a 3-layer stratigraphic model comprising sand-clay-sand has been presented. In areas with comparatively thin upper sand layer, the placement of fill consisting of cohesionless materials of about 1.5m drastically reduces the induced load to a safe and allowable range thereby allowing shallow foundations with significant loading to be supported in the coastal zone.

Keywords: coastal zone, clay, stratigraphy, foundations

Introduction

The coastal zone of Nigeria (see Fig. 1) covers an estimated area of 6000 km^2. It is presently the nerve centre of petroleum and related industry. The intensification of petroleum related activities with resultant population pressure have resulted in rapid infrastructural development. In this circumstance, most structures are built without consideration of the superficial geology or the competence of the foundation soil. There are now wide spread failures that are mostly attributed to foundation failure and excessive consolidation settlement of underlying compressible soils.

The conventional method of foundation design is based on the concept of bearing capacity or allowable bearing pressure of the soil. The bearing capacity is defined as the load or pressure developed under the foundation without introducing damaging movements in the foundation and in the superstructure supported on the foundation. Damaging movements may result from foundation failure or excessive settlement. To ensure safety and stability of foundation, two criteria are generally used in the design of foundation. These are (Gopal and Rao 2005):

(a) Determination of bearing capacity of soil and the selection of adequate factor of safety, usually not less than 2.5
(b) Estimating the settlement under the expected load and comparison with the permissible settlement

Reliable and simplified relationship for evaluating the ultimate net bearing capacity q_{nu} of a shallow strip foundation in a uniform, isotropic and homogenous soil are severally available (Gulhati 2005, Barnes 2000, Gopal and Rao 2005). These relations are essentially similar to that given by Terzaghi et al (1996) which is in the form:

$$q_{nu} = CN_c + P_o (N_q-1) + 0.5\gamma BN_\gamma \text{ ....(1)}$$

where: γ = the bulk unit weight of the soil below the foundation level (kN/m^3)
C = the undrained shear strength of the soil (kN/m^2)
P_o is the effective overburden pressure at the foundation level (kN/m^2)
N_c, N_q, N_γ = Terzaghi's bearing capacity factors obtained from charts

This work investigates the problems of foundation design instigated by the stratigraphic peculiarity of superficial geology in the coastal area of Nigeria.

Methods of study

Three localities, namely Bonny, Brass and Okrika which typify the coastal zone were identified and studied closely. Both field and laboratory techniques were used for this study. The field investigations involved boring and cone penetration sounding. At least, three boreholes were drilled at each location. Each borehole was advanced using a dismantleable percussion rig. The advantages of this rig for swamp operations includes ease of dismantling and assembling, light weight and ease of conveyance through the tropical forests (George and Abam, 1992). The soil sampling procedures adopted for this study, which were essentially in line with BS 5930 (1990), involved the regular collection of disturbed samples at intervals of 0.75 m and also when a change of soil type is observed. All samples recovered from the boreholes were examined, identified and roughly classified. A range of laboratory tests based on BS 1377 (1990) were also carried out.

A manually operated 25 kN capacity mechanical mantle cone penetrometer was used for the cone soundings. The high degree of densification of surface sand deposits in Bonny and Brass, with consequent low penetration, discouraged cone penetrometer test (CPT) tests at these locations.

Results

Site Geology

The coastal zone of Nigeria is dissected by river systems discharging into the ocean. NEDECO (1961) and NDES (1999) described the general geology of the area as essentially reflecting the influence of movements of rivers and their search for lines of flow to the sea with consequent deposition of transported sediments. This complex hydrological processes, involving flow, erosion and deposition of sediments has in the intervening geological time yielded "sandy islands" (Allen 1965). These islands which are also the densely populated centers are generally surrounded by mangrove swamp forests and belong to the Pleistocenic Formation. These islands are typified by Bonny, Brass and Okrika (see Fig. 1).

The surface deposits in these coastal zone islands comprise essentially sand. However, the general stratigraphy consists of an alternating sequence of sand and clay, with clay frequently occurring within the top 10m of the strata and often in a weak and soft consistency. The stratigraphy in these islands within the depths of engineering significance are presented as Figs. 2 - 4. The upper sands are predominantly medium to coarse in grain sizes, fairly uniformly graded and found to exist in mostly loose to medium dense states of compaction. At the fringe of the coastline as in Bonny and Brass, these sandy deposits become medium dense to dense in relative density due to their exposure to repeated tidal and wave compaction.

In broad terms and for purposes of model description, each of these sites could be rationalized as underlain by at least three primary soil zones. A sand layer, whose upper part is loose or dense depending on its location. Beneath the sand is usually a layer of soft clay with variable thickness. Underlying the clay is another deposit of sand.

Upper Sandy Horizon

The sand is uniformly graded and mostly loose to medium dense. In the coastal fringe it is mostly dense due to repeated tidal and wave loading. The standard penetration test (SPT) N-values which are also reflected in Figs. 3 and 4 indicate that an average angle of shearing resistance of 30^o were computed for this sand deposit using empirical correlations by Wolff (1989). By this method, SPT (N) values are corrected to a standard value of σ^1 [$95.6 kN/m^2$ ($1 ton/ft^2$)] , before substitution into the equation:

$$\phi \text{ (Deg.)} = 27.1 + 0.3 N_{cor} - 0.00054 N^2_{cor} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $N_{cor} = C_N N_F$

C_N = Correction factor

N_F = N value obtained from the field

.

Soft Clay

The clay beneath the upper sand is predominantly of low plasticity according to the Unified Soil Classification System and dark gray in colour. The dark gray coloration is mostly ascribed to its rich organic content. The engineering properties of this clay are summarized in Table 1.

Table 1: Index properties of the soft clay

Soil Property	**Average value**
Natural moisture content (%)	35.5
Liquid limit (%)	49.7
Plastic limit (%)	23.1
Plasticity index (%)	26.6
Bulk unit weight (kN/m^3)	18.2
Degree of saturation (%)	100
Specific gravity	2.60
Initial void ratio	0.68
Undrained cohesion (kPa)	12
Undrained angle of shearing resistance (^{0})	10

Lower Sandy Horizon

Below the soft clayey soil is a relatively clean, medium to coarse-grained, uniformly-graded sand deposit. The SPT N-value for the sand layer indicates that it is loose to medium dense in relative density. Average angle of shearing resistance of 30^0 was obtained for this sand deposit based on Wolff (1989).

Since the sandy horizon consisted of clean, rounded and uniformly graded particles, empirical methods of permeability determination based on particle size distribution are expected to give realistic estimates (Barnes, 2000). Consequently, coefficients of permeability were calculated for both upper and lower sandy layers using the relationship (Murthy 1984):

$$k = C^1 (D_{10})^2 \times 10^{-4} \text{ m/sec} \quad \ldots\ldots(3)$$

Where $C^1 = 100 - 150$
D_{10} in mm

This assessment confirmed the sandy layers to be of high permeability generally between 4.68×10^{-5} m/sec to 2.3×10^{-3} m/sec.

Discussions

Foundation construction on the surface of sandy deposit results in frequent foundation failures, not because of the incompetence of the sandy layer, but the proximal occurrence of soft, weak and compressible clay which bearing characteristics is often disregarded. The contribution of the total settlement of such clay layers depends on the depth of occurrence, thickness of the deposit and its coefficient of volume compressibility. This study considers the occurrence of this soft and compressible clay as a stratigraphic constraint to shallow foundation design and construction.

Consider the generalized stratigraphy (see Fig. 5), which has been shown to be characteristic of the coastal zone.

Two approaches may be adopted for this 3-layer case in which the weaker clay is sandwiched between sandy layers and located close to the ground surface.

i). Calculating the bearing capacity of the top layer and assessing the impact of the induced load at the top of the weaker layer.
ii). Considering the soft and weak clay layer as the critical layer and assessing its bearing capacity with respect to the imposed load.

The later approach result to an over-design which invariably involves a higher cost outlay. Conservative results are obtained if the soft clay layer occurring at shallow depth constitutes the critical layer for shallow foundation when estimating the bearing capacity of the foundation. Since this clay layer is close to the ground surface, it is therefore likely to be adversely affected by the load induced by the structure on a shallow foundation.

For such cases, Tomlinson (1999) gives the bearing pressure q_1 on the surface of the soft clay for strip or pad foundation as:

$$q_1 = \Delta\sigma_n \left(\frac{B}{B + d} \right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where: $\Delta\sigma_n$ the surcharge load (kN/m^2)
B = width of footing (m)
d = depth from foundation base to clay layer (m)

As a basis for foundation design, a factor of safety (FS) can be defined in which the bearing capacity of the shallow and weak clay is related to the induced load at the top of the sand layer. Such an expression for factor of safety will take the form:

$$FS = \frac{CN_c + P_o (N_q - 1) + 0.5\gamma B N_\gamma}{\Delta\sigma_n \left(\frac{B}{B + d} \right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

This factor of safety will indicate the ability of the weak clay soil to support the induced load. If it is assumed that this clay has no frictional component, then the above equation can be reduced to dimensionless coefficients:

$$\left(\frac{B}{B + d} \right) = \frac{5.14\ C}{FS\ \Delta\sigma_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

which can then be graphically represented by Fig. 6 for different factors of safety. The importance of Fig. 6 is the convenience with which a shallow foundation can be designed based on the knowledge of undrained cohesion and the depth to the top of the weak soft layer and the imposed load.

For instance, if we consider a foundation load of 60 kN/m^2 on a strip foundation over a soil profile in which a clay soil with undrained cohesion of 10kN/m^2 is at 1m below the ground surface. The coefficient $C/\Delta\sigma_n = 0.2$. If a factor of safety against the failure of the clay layer is desired, then based on Fig. 6, $B/(B+d) = 0.5$. This then implies that the width of the strip or pad foundation can be obtained from the relationship: $B = 0.5B + 0.5$, which translates to B = 1m.

Although the overlying stiff soil may have a reasonably high shear strength and relatively high allowable bearing pressure, the foundation would be placed very close to the underlying soft clay for the foundation load transmitted through the stiff layer to exceed the safe bearing pressure of the soft material. If the allowable bearing pressure of the soft clay is less than 10 kN/m^2, clearly, the bearing capacity of the soft clay will be exceeded by the induced pressure thereby increasing the prospect of foundation failure.

The mitigative options available include:-

(i). Sand filling to a height of between 1.5 m - 2.0 m and using a shallow pad foundation. For each fill increment the bearing pressures exerted on the clay will be further reduced. Table 2 gives the reduction in induced load of 60 kN/m^2 over a soil profile with different depths to a weak clay layer.

Table 1. Reduction in loading on top of clay after placement of fill

Fill Height (m)	Stress induced on soft clay x $\Delta\sigma_n$ (kN/m^2)	Bearing Pressure for 60 kN/m^2 surcharge
0.5	0.44	26.4
1.0	0.04	24.0
1.5	0.36	21.6
2	0.33	19.8
2.5	0.31	18.6

It is expected that the applied pressure can still be further reduced if the footings of the foundation are combined to form a rigid frame or raft foundation. While the pad foundation may seem satisfactory for large sections of the foundation, towers which exert a load in excess of 150 kN/m^2 would require Piling through the soft layer to the deeper loose medium - dense sand layer, where the piles are able to mobilize adequate bearing capacity. An alternative to piling will be a large caisson structurally connected to the frame of the pad foundation that will extend below the soft clay layer. However, this is not common in the study area, due perhaps to the high cost and the rarity of specialized technology required for its construction. The special foundation of the tower, takes cognissance of the large wind stresses that tall structures are exposed to, by reason of height and coastal location.

Conclusions

The coastal areas of Nigeria are characterized by an alternating sequence of sand and clay in which a soft clay occurs at shallow levels that are frequently impacted by surface loads. The feasibility of adopting shallow foundation for structures was assessed by the depth to and bearing pressure at the top of the critical soft clay layer.

A chart was developed in terms of dimensionless coefficients which simplifies the process of shallow foundation design for various combinations of ($C/\Delta\sigma n$) and ($B/(B+d)$). In view of the probable low allowable bearing pressure in these areas for strip foundation, a pad foundation has been recommended for foundations with significant loading. However, where heavier loads such as from towers or concentrated loads a pile foundation or a caisson may be used. The footings of the pad foundation are to be structurally linked to form a well reinforced rigid frame in order to reduce the consequent consolidation settlement of any intervening compressible layers.

References

Allen, J. L. (1965) Late Quaternary Niger Delta and adjacent areas sedimentary environment and lithofacies *AAPG Bull* 49:54-60
Barnes G.E (2000) Soil mechanics : Princples and practice, 2nd edition, Palgrave, MacMillan 493pp
Bowles T.E (1997) Foundation Analysis and Design.Mc.Graw-Hill international Editions.
British Standard Institutions BS 5930 (1981) Code of Practice for Site Investigation, London.
British Standard Institutions BS 1377 (1990) Methods of Tests for Soils for Civil Engineering Purposes, London
Das, B.M (1999) Principles of Foundation Engineering, 4th Edition, Purs Publishing, 862pp
Garg, S.K. (2005) Soil mechanics and foundation engineering, Khanna publishers, Delhi, 1199pp
George E.A.J and Abam T.K.S. (1992) Soil exploration strategies in the Niger delta. Proceedings of 1st Int. Conf. On constructions on polluted and marginal lands, London, edt. M.C. Forde, pp 6-9
Gopal R and Rao A.S.R (2005) Basic and applied soil mechanics, Newage International publishers, 761pp
Gulhati S.K and Datta M.J (2005) Geotechnical engineering, McGrawHill Company 738pp
Murthy V.N.S (1984) Soil Mechanics and Foundation Engineering, Dhanpart Rah and Sons , India.763pgs.
Netherlands Engineering Consultants NEDECO (1961) Water of the Niger, The Haque
Niger Delta Environmental Survey NDES (1999) Physical Environment Report on the Hydrology of the Niger Delta, Vol. 2, 255pp
Terzaghi K ;Peck, R.B and Mesri, G (1996) Soil Mechanics in Engineering Practice. 2nd Edition John Wiley and Sons 724pgs.
Tomlinson M. J (1999) Foundation Design and Construction 6th Edition, Longman, 536 pp

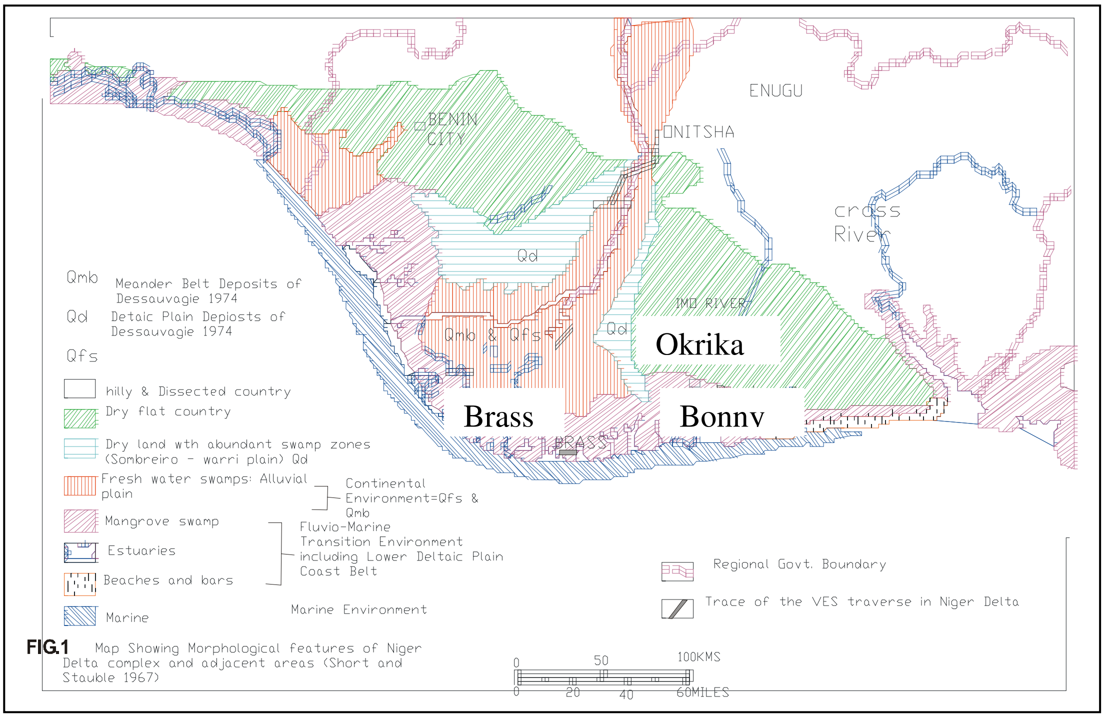

Fig. 1: Map of coastal area of Nigeria, showing locations of study

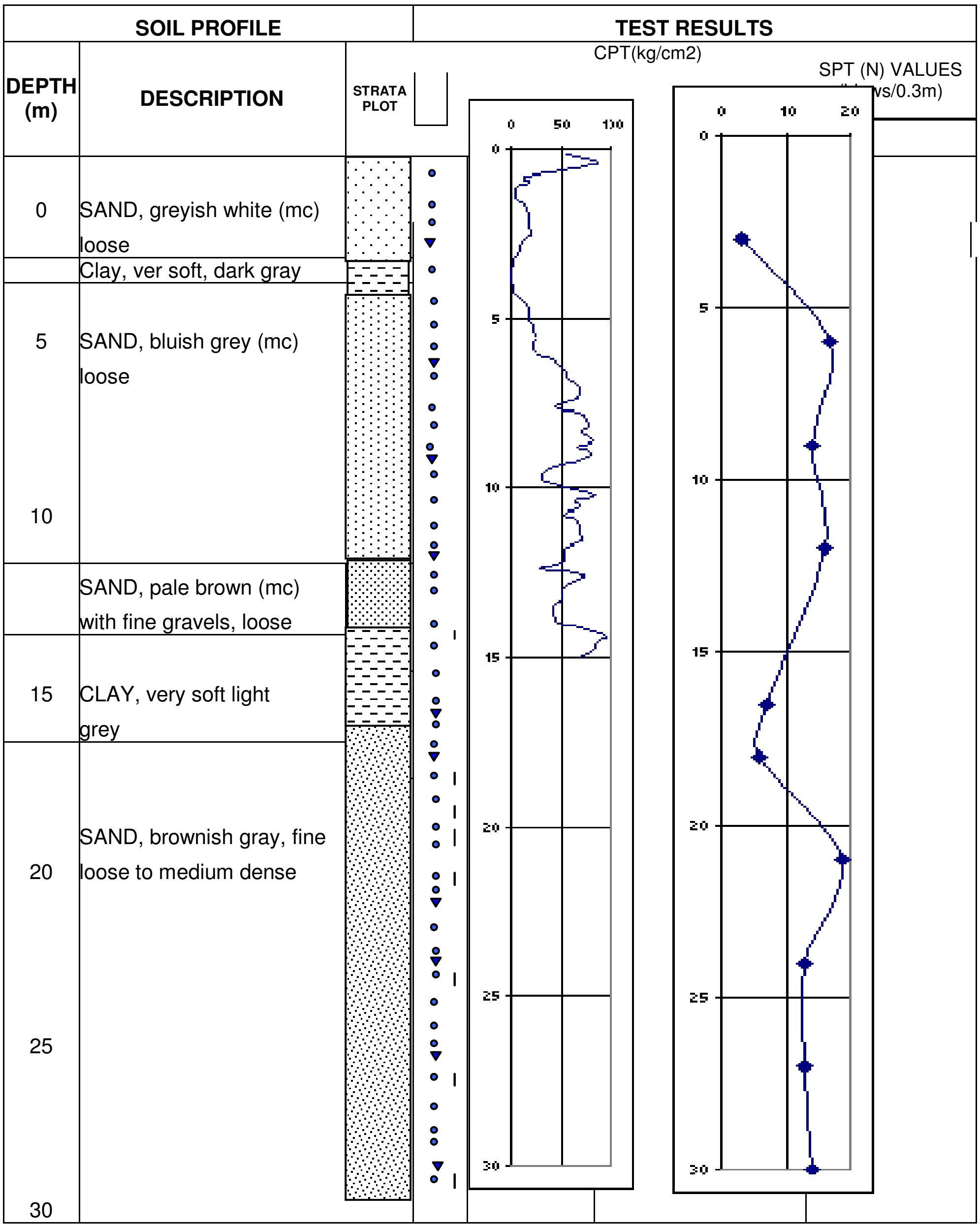

Fig. 2 Typical soil profile in the Okrika sandy island at the coastal zone

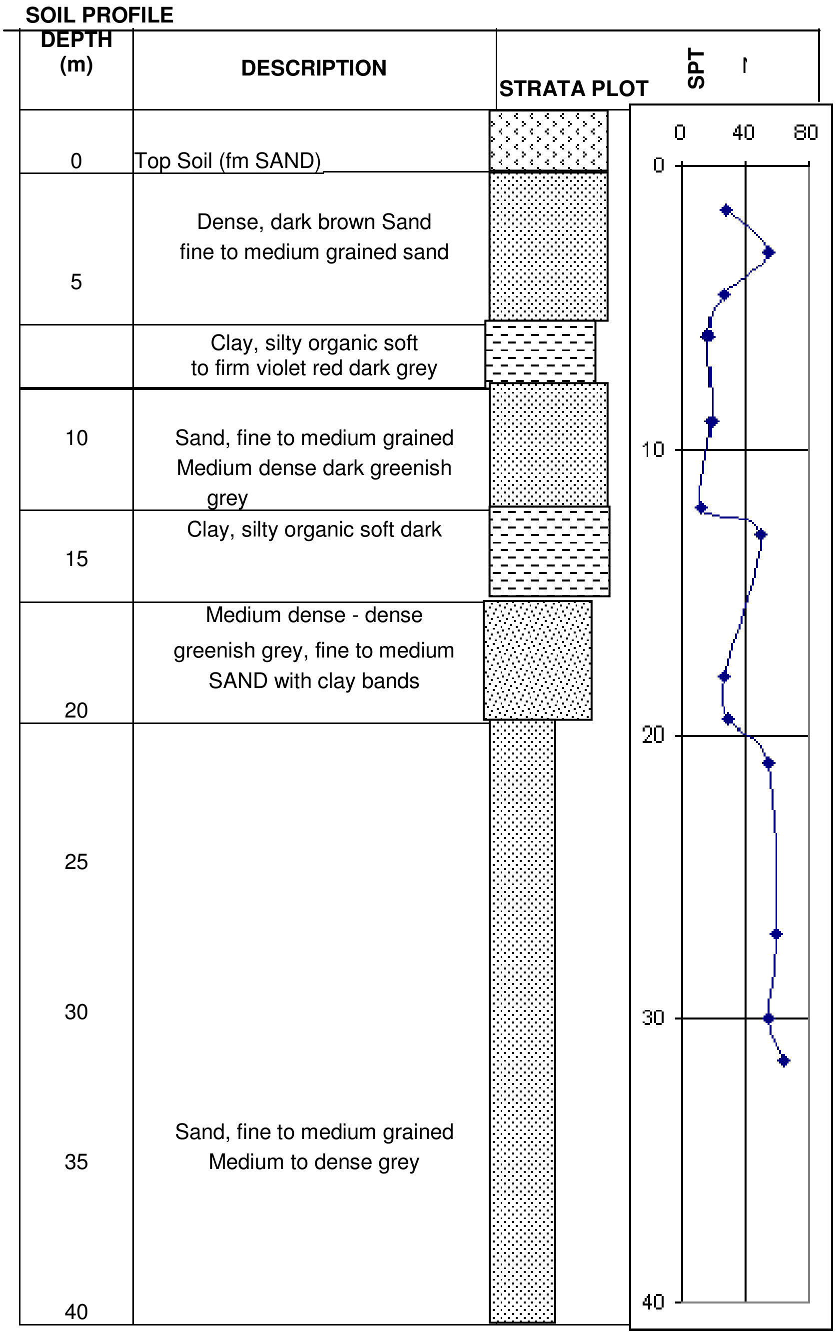

Fig. 3 Typical soil profile in the Brass sandy island at the coastal zone

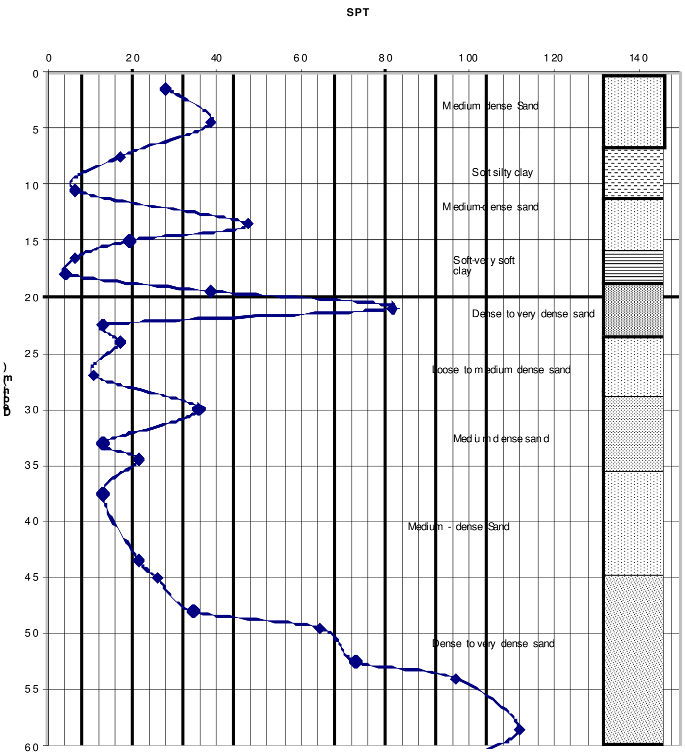

Fig. (4) Typical Litholog and SPT-N value variation with depth in a Mangrove Swamp

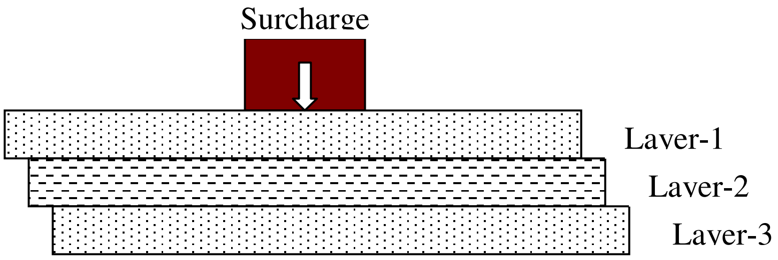

Fig. 5 Generalized stratigraphy of the coastal zone

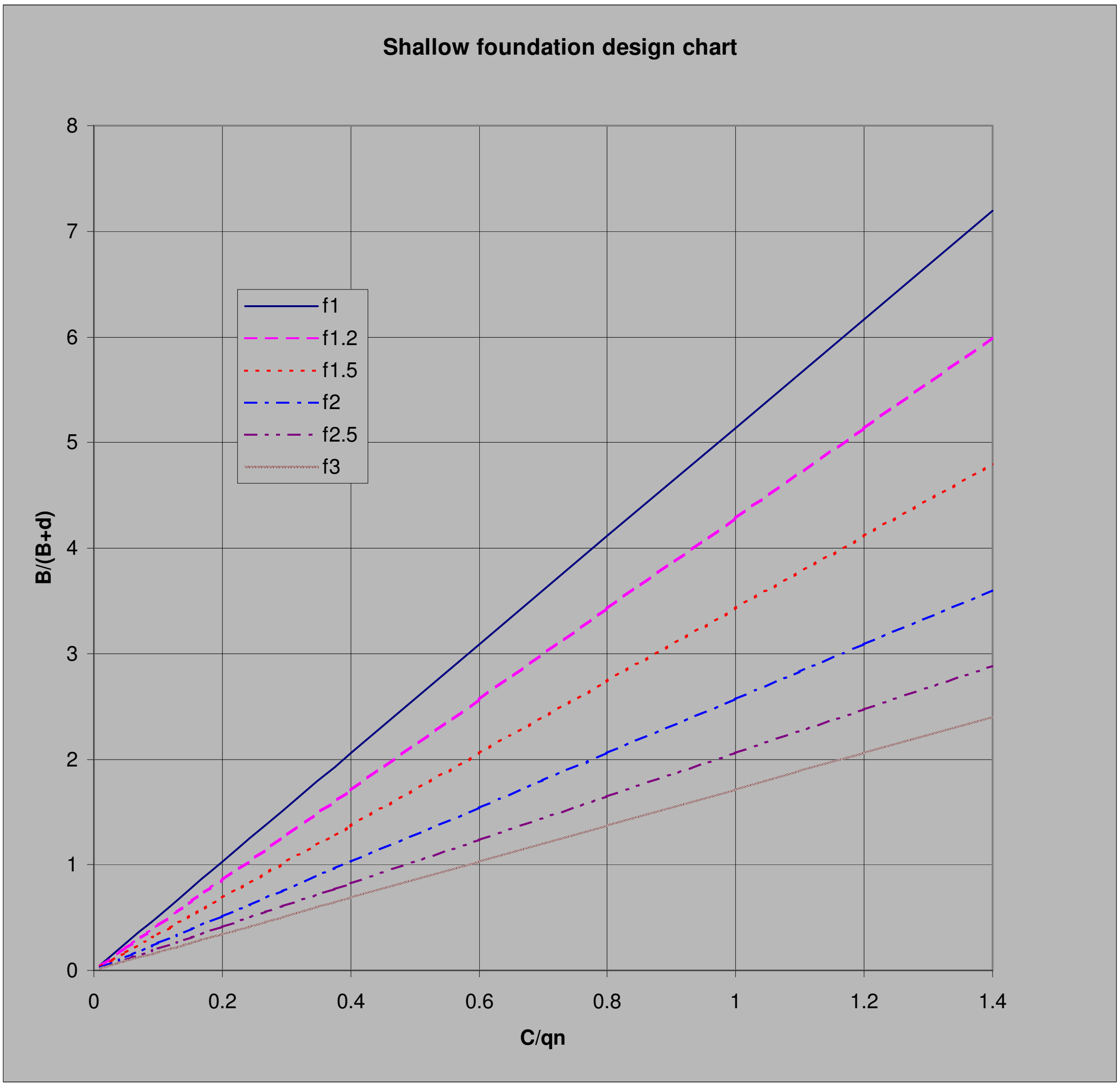

Fig. 6 Foundation design chart for a typical case