Shallow Foundation Analysis on Heterogeneous Soil Formation in the Niger Delta of Nigeria

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Abstract

Assessment on the stability and deformation requirements of shallow foundations on heterogeneous soil formation was carried out, using both field exploration and laboratory analysis. Results showed that based on site topography a Raft foundation can be placed on top of the overlying clay layer and subsequently backfilled to meet the adjacent highway grade level. However, the raft foundation exceeded the maximum permissible deformation requirement. A compromise on stability and deformation requirements was reached by either increasing footing dimension or placing the Raft foundation on the underlying cohesionless silty and slightly silty sand formations at one meter below ground level.

Key words: Stability. Deformation. Stress Analysis.

Introduction

The two basic criteria to be satisfied in the analysis and design of a shallow foundation are stability and deformation requirements. Stability requirement ensures that the foundation does not undergo shear failure under loading, while deformation requirement ensures that settlement of a structure is within the tolerance limit of the superstructure. Consequently, an assessment of foundation stability and deformation requirement on any given site is of utmost priority, knowing the devastating cost of failure. Some studies on stability and deformation of foundations have been reported by scholars including Terzaghi (1943); Vesic, (1973); Akpila (2007a); Akpila (2007b) and Akpila et al. (2008). This paper attempts to report on analysis of shallow foundations on heterogeneous soil formation in the Niger Delta of Nigeria.

Materials and Method

Field Exploration/ Laboratory Analysis

Subsurface conditions at the site were studied through ground borings to depths of 15m using a percussion boring rig. Both disturbed and undisturbed samples were collected for visual examination, laboratory testing and classification. Standard Penetration Tests (SPT) was also conducted to determine the penetration resistance values of sand bodies at specific depths within the boreholes. Requisite laboratory tests on soil samples to obtain input parameters for stability and deformation assessment were conducted. The water table varies from about 1.7-1.8.0m depth below the existing ground level.

Bearing Capacity

Two foundation options were attempted.

Raft Foundation on upper clay layer

A bearing capacity analysis for a Raft foundation has been necessitated by the soil stratigraphy at site having about one metre (1m) of soft clay, overlying sand formation. The proposed Raft foundation is to be placed on the overlying clay layer and subsequently backfilled to at least 1.2m, being the elevation difference between the crown level of the existing highway pavement and the project location.

The net ultimate bearing capacity of the raft foundation on purely cohesive soil under vertical loading is given by the expression (Meyerhof, 1963)

$$q_{n(u)} = c_u N_c F_{cs} F_{cd}$$
$$= c_u N_c \left[1 + \frac{B}{L}\left(\frac{N_q}{N_c}\right)\right]\left[1 + 0.4\left(\frac{D_f}{B}\right)\right] \quad (1)$$
$$q_{n(a)} = \left\{c_u N_c \left[1 + \frac{B}{L}\left(\frac{N_q}{N_c}\right)\right]\left[1 + 0.4\left(\frac{D_f}{B}\right)\right]\right\}/FS \quad (2)$$

where

$q_{n(U)}$ = net ultimate bearing capacity
$q_{n(a)}$ = net allowable bearing capacity
c_u = undrained cohesion
N_c,N_q = bearing capacity factors with respect to cohesion and surcharge respectively
F_{cs} = shape factor with respect to cohesion
F_{cd} = shape factor with respect to depth
B, L= breadth and length of foundation respectively
D_f = depth of foundation
FS = factor of safety

For cohesive soil (ϕ=0), and for D_f = 0(foundation is placed on the clay layer);

$$q_{n(u)} = c_u N_c \left[1 + 0.195\frac{B}{L}\right] \quad (3)$$

Giving that B=11m and L= 55m, yield the following;

$$q_{n(u)} = c_u N_c \left[1 + 0.195\left(\frac{11}{55}\right)\right]$$
$$= 1.04 c_u N_c \quad (4)$$

For ϕ = 0, N_c = 5.14. Also using a factor of safety, FS, = 3.0;

$$q_{n(a)} = 1.787 c_u \quad (5)$$

The net allowable bearing capacity of the proposed Raft foundation can be evaluated from Equation (5).

Isolated Pad foundation placed on top of underlying SAND layer

The net ultimate bearing capacity of a square foundation on sand is given by the expression (Terzaghi, 1943);

$$q_{n(u)} = \gamma' D_f \left(N_q - 1\right) + 0.4\gamma B N_\gamma \quad (6)$$

where N_γ,N_q are the dimensionless bearing capacity factors proposed by Vesic (1973) and γ' is submerged unit weight of soil.

The net allowable, $q_{n(a)}$, bearing capacity of the soil has been evaluated for a factor of safety (F.S) of 3.0 being applied on the net ultimate bearing capacity while the submerged unit weight is used to account for the effect of water table on bearing capacity. A comprehensive discussion on the use of bearing capacity factors has been presented by Matawal (1991).

Isolated Pad foundation placed on top of underlying SAND layer
(SPT Approach)

The modified Meyerhof (1956) correlation for bearing capacity using Standard Penetration Resistance is presented by Bowles (1977) as follows:

$$q_{n(a)} = 19.16 N F_d \left(\frac{s}{25.4}\right) \qquad for\ B \le 1.2m \quad (7)$$
$$q_{n(a)} = 11.98 N \left(\frac{3.28B + 1}{3.28B}\right)^2 F_d \left(\frac{s}{25.4}\right) \quad for\ B > 1.2m \quad (8)$$

where F_d = depth factor = 1+ 0.33 (D_f/ B) ≤ 1.33
s = tolerable settlement
N = average penetration number

Stress Analysis

Induced vertical stress analyses was based on a stress distribution of 2:1 spread at either the centre of a compressible stratum or at the interfaces of two soil formations where ever applicable. The induced vertical stresses were analysed from the expression;

$$\Delta\sigma_z = \frac{\sigma_1 LB}{(B+z)(L+z)} \quad (9)$$

where

$\Delta\sigma_z$ = Induced vertical stress at centre of consolidating layer

σ_1 = initial bearing pressure

B, L = footing dimensions

z = depth of interest

Settlement Analysis on upper clay layer

Immediate Settlement

Immediate settlement has been computed for a raft foundation of 11m x 55m dimension, placed on top of clay formation being underlain by sand. The immediate foundation settlement can be obtained from the expression (Tomlinson, 2001).

$$S_i = \frac{Bq_n}{E}\left(1-\mu_s^2\right)I_p \quad (10)$$

where

S_i = immediate settlement

B = breadth of foundation

q_n = net foundation pressure

E = modulus of elasticity,

μ = Poisson ratio.

I_p = influence factor

For saturated clays, μ = 0.5 and $I_p = F_1$. Modulus of elasticity is computed from the expression proposed by Butler (1974).

$$E/c_u = 400 \quad (11)$$

Consolidation Settlement on upper clay layer

Total settlement (ρ_c) in the cohesive layer has been computed based on the foundation breadth (B) subjected to a bearing pressure of 45kN/m^2 and m_v value of 0.93m^2/MN. The settlement value can be computed from the expression given by Skempton and Bjerrum (1857) as follows:

$$\rho_c = \frac{\Delta e}{1+e_o}\left(\frac{1}{\Delta p}\right)\Delta\sigma_z H$$

$$= m_v \Delta\sigma_z H \quad (12)$$

where

ρ_c = consolidation settlement in the cohesive layer

m_v = coefficient of volume compressibility

$\Delta\sigma_z$ = induced vertical stress at centre of consolidating layer

H = thickness of consolidating layer

Settlement on sand

The settlement per unit pressure on sand was analysed using the method presented by Burland, Broms and De Mello (Craig, 1987). An induced vertical stress increment of 41kN/m^2 exerted on the clay- sand interface from the Raft foundation was adopted in the analysis.

Consolidation Settlement on lower clay layer

A bearing pressure of 45kN/m^2 from the Raft foundation was imposed on the top clay layer. Adopting a pressure distribution of 2:1, an induced vertical stress of 28.4kN/m^2 at the centre of the 2m thick compressible clay layer and located at 4-6m depth was used to obtain the total consolidation settlement. Consolidation settlement is computed using Equation (13).

The total settlement from the Raft foundation can be obtained from the expression;

$$\rho_t = \rho_{i(\text{top clay})} + \rho_{c(\text{top clay})} + \rho_{i(\text{sand})} + \rho_{c(\text{lower clay})} \quad (13)$$

while allowable settlement values for different structures have also been presented by scholars including Skempton and MacDonald (1956), Polshin and Tokar(1957), and Wahls (1981).

Discussion of Results

Soil Classification

The soil generally consist of soft, brown and grey CLAY, very silty CLAY, medium - dense silty SAND and slightly silty SAND found at various depths

Soil Stratification

The soil profile generally consists of soft, brown, low to intermediate plasticity CLAY of about 1m thickness, underlain by medium-dense, brown, silty to slightly silty SAND from 1- 4m depth. This formation is immediately underlain by soft, grey, low to intermediate plasticity CLAY from 4 - 6m depth (BH1) but low plasticity very silty CLAY from 4-5m depth (BH2). Below this formation is medium - dense, grey to brown, silty to slightly silty SAND (BH1), but brown, silty to slightly silty SAND (BH2) up to the 15m depth of exploration. Details of soil characteristics and foundation loadings are presented in Figures 1 and 2.

Bearing Capacity

An undrained cohesion, c_u, of 25kN/m^2 was generally obtained on the top clay formation, resulting to a net allowable bearing capacity of 45kN/m^2 for a Raft foundation of 11m x 55m placed on top of the clay layer. Bearing capacity results for isolated Pad footing placed 1m below ground formation are presented in Tables 1 and 2.

Settlement Analysis

Immediate Settlement on upper clay layer

An influence factor of 0.01 is obtained at the centre of raft foundation of 11m x 55m dimension. With an average undrained cohesion of 25kN/m^2, a modulus of elasticity 10,000kN/m^2 was obtained from Equation (11). The immediate settlement at centre of the foundation (Equation 10) under a net foundation pressure of 45kN/m^2 gave a value of approximately 1.0mm.

Consolidation Settlement upper clay layer

An induced vertical stress of 43kN/m^2 is obtained at the centre of the consolidating top clay layer for a net foundation pressure of 45kN/m^2 under a vertical stress distribution of 2:1 spread. For a coefficient of volumetric compressibility, $m_{v,}$ of 0.93m^2/MN (Table 3), the consolidation settlement (Equation 12) in the cohesive layer is 42mm.

Settlement on sand

An induced vertical stress increment of 41kN/m^2 is exerted on the clay- sand interface from the Raft foundation. This gave an upper limit of approximately 8 mm settlement and the unlikely 75% of maximum settlement value for the medium-dense sand is 6 mm.

Consolidation Settlement on lower clay layer

A bearing pressure of 45kN/m^2 was imposed on the top CLAY layer (BH1) from the Raft foundation. This bearing pressure resulted in an induced vertical stress of 28.4kN/m^2 at the centre of the 2m thick compressible clay layer located at 4-6m depth, using a pressure distribution of 2:1spread. A consolidation settlement of 52 mm is obtained for this layer.

The total settlement from the Raft foundation (Equation 13) gave a value of approximately 101 mm. However a maximum settlement value of 100mm is suggested by Skempton and MacDonald (1956) for Raft foundations on clay.

Conclusion

The heterogeneous nature of the site subsurface calls for an erudite and sound engineering judgment in construction practice. High settlement are associated with parts of the site as the lower compressible cohesive soil vary in nature and thickness, hence the two metres lower clay layer is selected in the settlement analysis. It is suggested that the intended Raft foundation dimension should be slightly increased to reduce the anticipated bearing pressure hence, the induced vertical stresses transferred to the underlying soil. However, to reduce the anticipated settlement the Raft foundation should be placed at the clay-sand interface of about one metres below ground level.

Table 1: Bearing Capacity

Depth of Foundation (m)	Foundation Breadth, B (m)	Unit Weight γ (kN/m³)	Average SPT value N	Angle of friction ϕ (degrees)	Net allowable bearing capacity (kN/m²)
1.0	**1.0** **1.1** **1.2** **1.3** **1.4** **1.5** **1.6**	19.8	10	30	87 90 93 96 99 102

Table 2: Bearing Capacity (SPT Approach)

Depth of Foundation (m)	Foundation Breadth, B (m)	D_f / B	Average SPT value (N)	Depth Factor F_d	Submerged Values of q_a (kN/m²)
1.0	**1.0**	**1.0**	**10**	**1.33**	**127**
	1.1	**0.90**		**1.29**	**123**
	1.2	**0.83**		**1.27**	**121**
	1.3	**0.76**		**1.25**	**114**
	1.4	**0.71**		**1.23**	**109**
	1.5	**0.66**		**1.21**	**104**

Table 3: One-dimensional Consolidation Test

Borehole No.	Depth of Sample (m)	Specific Gravity	Pressure Range (Kpa)	Coefficient of Volume Compressibility, m_v (m^2/MN)
1	**1.0**	**2.70**	**0 – 25**	**1.20**
			25 – 50	**0.93**
			50 - 100	**0.46**
			100 – 200	**0.30**
			200 - 400	**0.15**
			400 - 800	**0.08**
	5.0	**2.60**	**0 – 25**	**2.00**
			25 – 50	**0.91**
			50 - 100	**0.61**
			100 – 200	**0.41**
			200 - 400	**0.26**
			400 - 800	**0.16**
2	**4.0**	**2.70**	**0 – 25**	**0.50**
			25 – 50	**0.60**
			50 - 100	**0.39**
			100 – 200	**0.24**
			200 - 400	**0.11**
			400 - 800	**0.07**

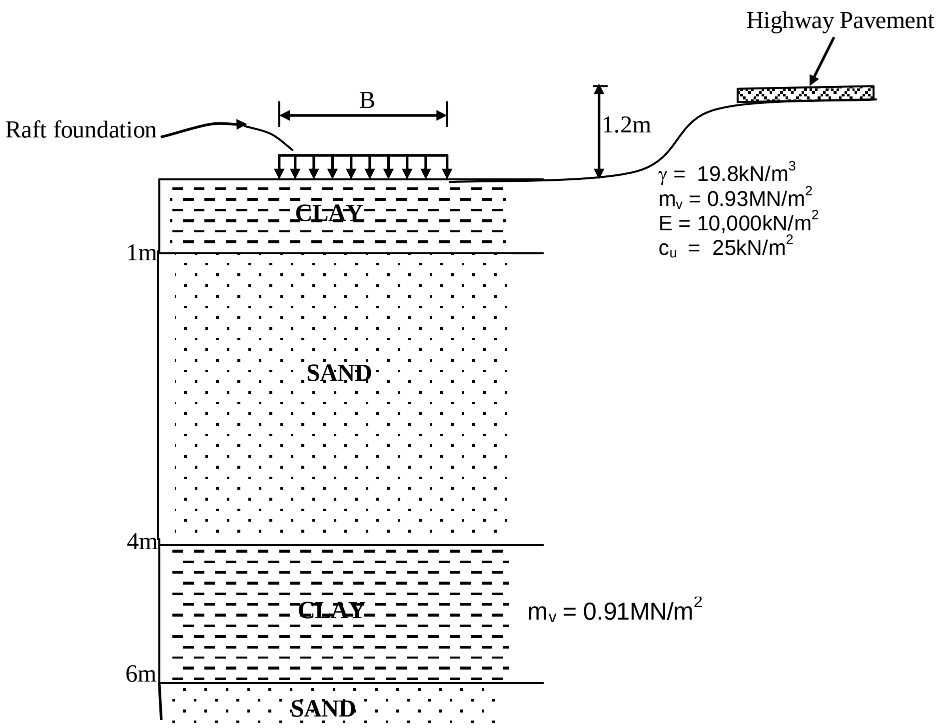

Figure 1: Raft foundation on heterogeneous formation

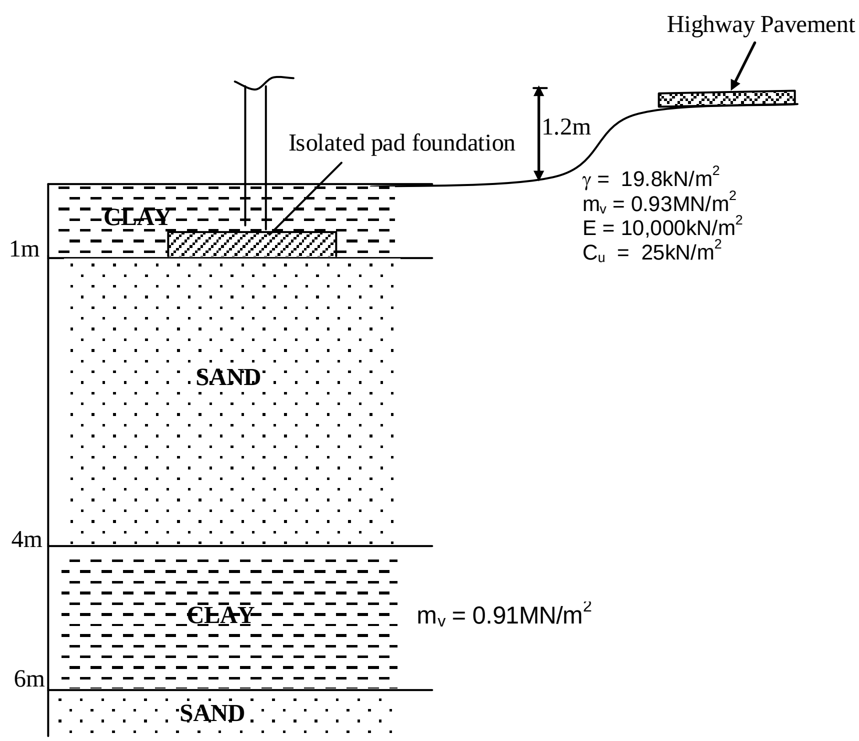

Figure 2: Pad foundation on heterogeneous formation

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