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Influence of Settlement on Bearing Capacity Analysis of Shallow Foundations on Sandy Clays in the Niger Delta, Nigeria

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ABSTRACT

The influence of foundation settlement on appropriation of bearing capacity of shallow footings on sandy clays has been studied through deep subsurface borings, laboratory tests and analysis. Generally, allowable bearing capacity values vary from 73-86kN/m^2 for raft foundation breadth of 19.3m and 29.5m up to 3m depth below ground level. Values of immediate settlement, S_i, for foundation breadths of 19.3m and 23.3m were 6mm and 7.2mm respectively for a bearing pressure of 50kN/m^2, while immediate settlement of 9.6mm and 11.7mm were respectively obtained for a bearing pressure of 80kN/m^2. Total settlement values ranged from 64-91mm under a bearing pressure of 50kN/m^2 as foundation depth decreases. For higher bearing pressure of 80kN/m^2, total settlement values ranged from 103-146mm with decrease in foundation depth. For satisfactory deformation requirement, a bearing pressure of 50kN/m^2 gave settlement values satisfying the maximum allowable limits for mat foundations on clays, while 80kN/m^2 gave excessive settlement values.

Keywords:. Deformation, Bearing Pressure, Shear failure, Poisson Ratio.

INTRODUCTION

Shallow foundations placed on compressible soil formation are required to satisfy both stability and deformation criteria in foundation analysis and design. Stability criterion ensures that the anticipated induced bearing pressure from the foundations do not cause shear failure of supporting soil under loading, while deformation requirement ensures that the generated vertical volume change on the soil is within the tolerance limit of the superstructure. Three types of shear failures have been identified to occur under foundation induced loading; general shear failure, punching shear failure and local shear failure. Details of their failure mechanisms are available in literatures [1, 2, 3, 4, 5]. The deformation response in cohesive soils is both immediate and time dependent. In the process of dissipation of excess pore water pressure in the cohesive soil structure, soil voids decreases resulting in vertical deformation; hence foundation displacement occurs.

Recent studies on the area of stability and deformation of shallow foundations in the Niger Delta of Nigeria reported the case of shallow foundation on sand overlying soft clay, having allowable bearing pressure $q_{a,}$ values ranging from 126-133kN/m^2, but 106-131kN/m^2 at soft clay-sand interface. For an induced bearing pressure of 95kN/m^2 and m_v of 0.26m^2/MN generated a total settlement of 12mm on 3m thick sand underlain by 4m thick clay [6, 7]. In the case of studies on two crude oil tank reservoirs in the Niger Delta with dimensions of 20m height and 18.8m diameter, gave a total settlement of 131mm and 148mm. At full capacity, it generated a net bearing capacity of 180kN/m^2 through metal plate placed on compacted sand [8, 9]. The methods of Perry, Meyerhof and modified Meyerhof on evaluation of bearing capacity of shallow foundation based on standard penetration test gave three bounds limits; upper, middle and lower bounds of net allowable bearing capacity for pad foundations on sand. The three bound limits occurred in the descending order of Perry, Meyerhof and Modified Meyerhof's method [10]. Shallow foundations placed on heterogeneous soil formations, gave deformation in excess of maximum allowable values for raft foundations on clays in the Niger Delta [11]. Also, specified limiting values for allowable settlement of raft foundations founded on either clay or sand formation have been presented by scholars in literatures [12, 13, 14].

This paper attempts to report on the role of shallow foundation deformation requirement in the adoption of an appropriate bearing pressure of a superstructure.

MATERIALS AND METHODS

Field Exploration/ Laboratory Analysis

Information about the subsurface conditions at the site was studied through ground borings to depths of 24m each using a light cable percussion boring rig. Both disturbed and undisturbed soil samples were collected for visual examination, laboratory testing and classification. Also, Standard Penetration Tests (SPT) was conducted to determine the penetration resistance of cohesionless strata at specific depths within the boreholes as borings advances. Requisite laboratory tests on soil samples were conducted to obtain input parameters for bearing capacity and settlement analysis. The water table was observed to vary from about 3.0-3.3m below the existing ground level at the period of investigation.

Bearing Capacity Analysis

A bearing capacity analysis of shallow foundation placed on soil formation consisting of soft, brown, low plasticity Sandy CLAY, overlying loose to medium-dense, slightly silty SAND formation was carried out. The proposed foundations were to be placed at one metre (1m) below ground level. The net ultimate bearing capacity, $q_{u(n)}$, is given by the expression[3];

$$q_{u(n)} = c_u N_c \left(1 + 0.3\, B/L\right) + \gamma' D_f \left(N_q - 1\right) + 0.5 \gamma' B N_\gamma \left(1 - 0.2\, B/L\right) \qquad (1)$$

Where c_u is undrained cohesion, B is foundation breadth, L is foundation length, γ is unit weight of soil, D_f is foundation depth, N_c and N_q are dimensionless bearing capacity factors [5]. 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 [15].

Settlement Analysis:

Stress Analysis

An induced vertical stress analysis was based on a stress distribution of 2:1, spread at either the centre of the compressible stratum [16]. The induced vertical stress was analysed from the expression;

$$\Delta\sigma_z = \frac{\sigma_{1LB}}{(B+Z)(L+Z)} \qquad (2)$$

Where, $\Delta\sigma_z\, is$ induced vertical stress at centre of consolidating layer, σ_1 is initial stress,

B, L are footing dimension, and z is depth of interest

Immediate Settlement

Immediate foundation settlement at a corner of a rigid raft foundation can be obtained from the expression [17] being reported in Braja [18] as follows;

$$s_i = \frac{q_{nB}}{E_o}(1-\mu^2) I_p \qquad (3)$$

Where; S_i is immediate settlement, B is breadth of foundation at a corner, q_n is net foundation pressure, E_o is modulus of elasticity, μ is Poisson ratio, I_p is influence factor for rigid foundation. To obtain the settlement at the centre of the foundation, the principle of superposition was adopted and settlement value is usually four times the settlement at any corner.

For saturated clays, μ=0.5 and I_p=F_1. Modulus of elasticity is computed from the expression [19];

$$\frac{E}{C_u} = 400 \qquad (4)$$

Consolidation Settlement
Consolidation settlement was carried out on the raft foundation using expression presented in the form [20]:

$$\rho_c = \frac{\Delta e}{1+e_o}\left(\frac{1}{\Delta p}\right)\Delta\sigma_z H$$
$$= \frac{\Delta e}{1+e_o}\left(\frac{1}{\Delta p}\right)\frac{q_{nBL}}{(B+Z)(L+Z)}H \qquad (5)$$

Where; ρ_c is consolidation settlement, q_n is net foundation pressure, B is foundation breadth, Δp is change in pressure, Δe is change in void ratio, e_o is initial void ratio, $\Delta\sigma_z$ is induced vertical stress, H is height of compressible layer, z is depth to point of induced vertical stress of interest and the term, $\frac{\Delta e}{1+e_o}\left(\frac{1}{\Delta p}\right)$ is coefficient of volume compressibility.

Total Settlement
Total foundation settlement can then be expressed as the summation of Equation (3) and Equation (5);

$$\rho_t = \frac{q_{nB}}{E_o}(1-\mu^2)I_p + \frac{\Delta e}{1+e_o}\left(\frac{1}{\Delta p}\right)\frac{q_{nBL}}{(B+Z)(L+Z)}H \qquad (6)$$

The limiting specification for mat foundations on soils forms the basis for assessment of vertical deformation on the foundation.

RESULTS AND DISCUSSION

Soil Classification / Stratification
Classification tests revealed the plastic soils as generally consisting of soft, brown, sandy CLAY of low to intermediate plasticity, underlain by loose to medium-dense, Slightly silty SAND as illustrated in Figure 1.

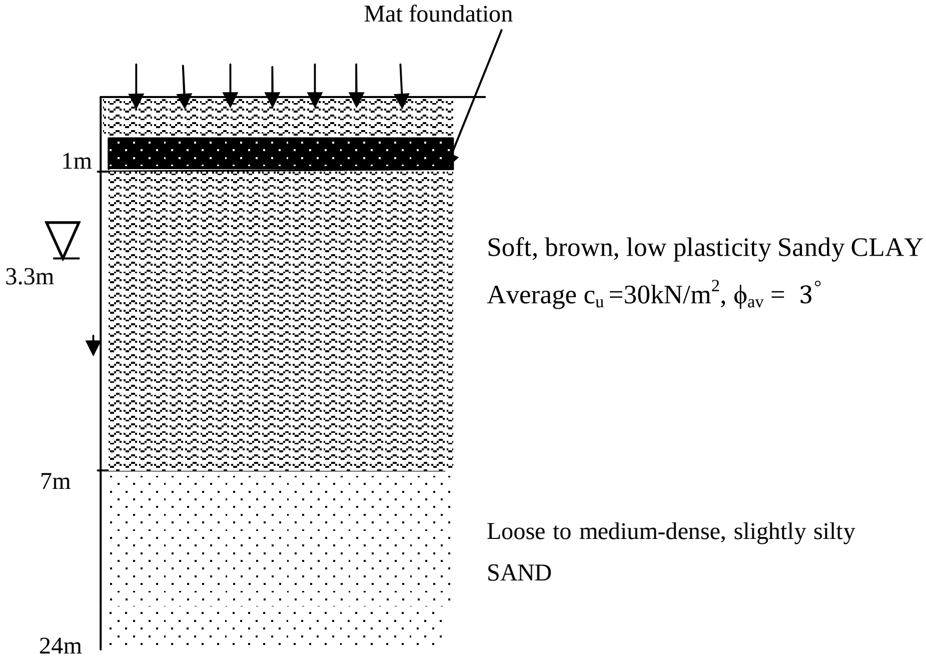

Figure 1: Mat foundation on typical soil lithology

Bearing Capacity
The allowable bearing capacity, q_a, for raft foundations with breadths of 19.3m and 29.5m, placed at different foundation depth, D_f are shown in Table 1. Generally, q_a, values vary from 73-84kN/m^2 and 73-86kN/m^2 for raft foundation breadth of 19.3m and 29.5m respectively up to 3m depth below ground level. The variation of allowable bearing capacity with varying foundation depths for foundation dimensions of B =19.3m and B = 23.3m are presented in Figures 2 and 3, while a typical mat foundation placed at 1m depth within the compressible soil formation is presented in Figure 1. A slight lateral variability in bearing capacity of soil is observed in the compressible soil lithology, while variability in bearing capacity values with depth at investigated points is almost

reproducible. However, for BH2, q_a, reasonably increased in value from 1.7m to 2.5m depth, beyond which the q_a values on BH1 and BH2 converged to 80kN/m^2 at 3m depth.

Settlement Analysis:

Vertical Stress

The induced vertical stress within a compressible soil thickness of 7m below ground was analyzed at varying foundation depth below ground level. A 2:1 stress distribution on the mat foundations were adopted under a bearing pressure of 50kN/m^2 and 80kN/m^2 on foundation dimensions of B_1 = 19.3 m, L_1 = 25.2 m and B_2 = 23.3 m, L_2 = 29.5 m. Details on the variation of induced vertical stress with foundation depth are presented in Figures 4 and 5.

Settlement on Mat foundation

The results of immediate settlement were analyzed for net foundation pressure of 50kN/m^2 and 80kN/m^2 from Equation (3). The modulus of elasticity was obtained from Equation (4) as 12000MPa, Values of immediate settlement, S_i, for foundation breadths of 19.3m and 23.3m were evaluated as 6mm and 7.2mm respectively for a bearing pressure of 50kN/m^2, while immediate settlement of 9.6mm and 11.7mm were respectively obtained for a bearing pressure of 80kN/m^2.

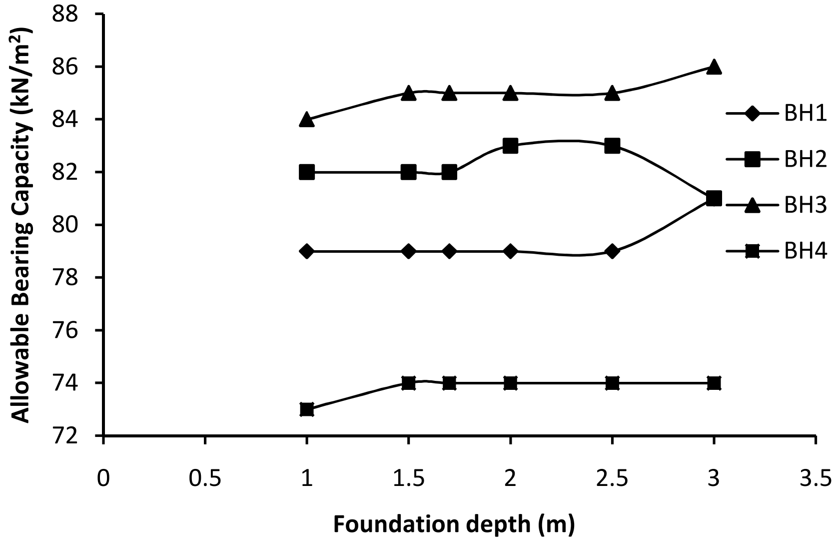

Figure 2: Variation of Allowable Bearing Capacity with Depth (B = 19.3 m, L= 25.2 m)

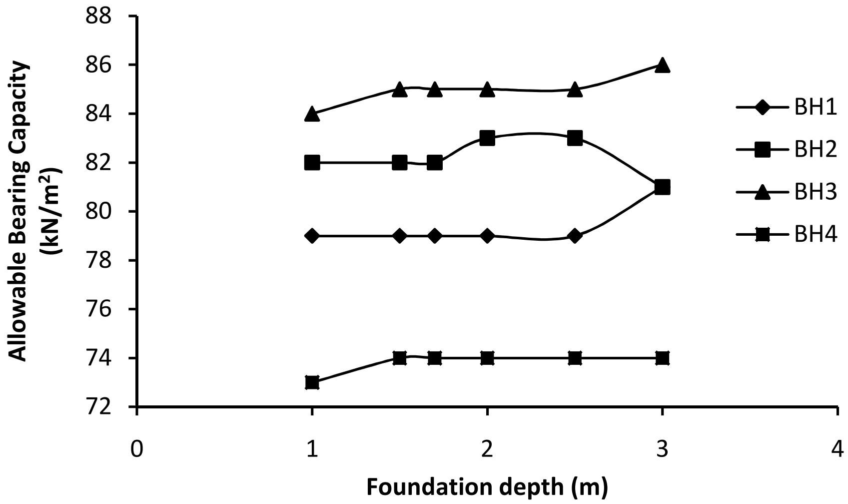

Figure 3: Variation of Allowable Bearing Capacity with Depth (B = 23.3 m, L= 29.5 m)

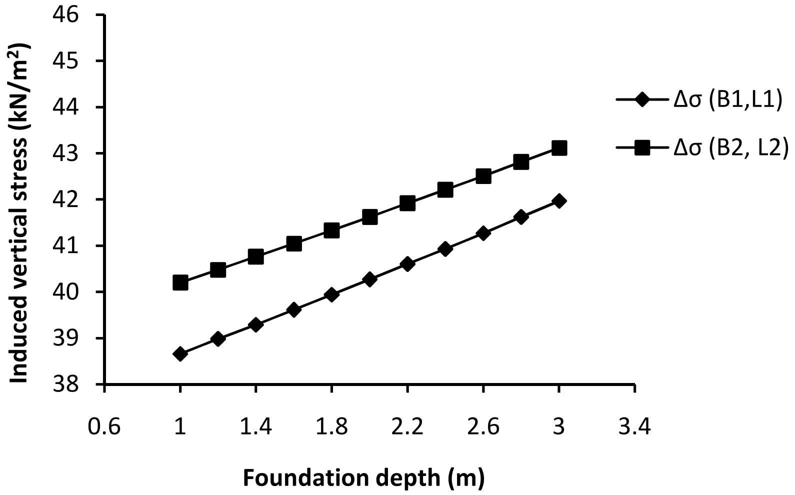

Figure 4: Induced vertical stress (2:1spread) with foundation depth for qn= 50kN/m^2

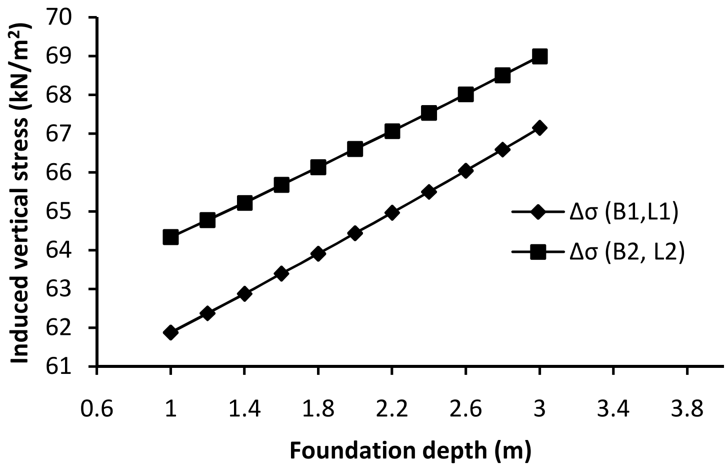

Figure 5: Induced vertical stress (2:1spread) with foundation depth for q_n = 80kN/m^2

The various response graphs of consolidation and total settlement are portrayed in Figures 6-9. Variation in consolidation settlement with increase in foundation depth showed a decreasing trend with lower values on B_1, L_1 as against B_2, L_2. Increase in foundation depth results in reduction on thickness of compressible clay thickness (H) which ultimately causes increase in induced vertical stress and subsequently a decrease in consolidation settlement.
Foundations under higher bearing pressure (80kN/m^2) generated higher values of consolidation settlement and total settlement; 94-135mm and 103-146mm respectively, with decreasing foundation depth while for a bearing pressure of 50kN/m^2, consolidation settlement and total settlement had values of 58-84mm and 64-91mm respectively, with decreasing foundation depth. Details of these are presented in Tables 2. For deformation requirement, the foundations subjected to a bearing pressure of 50kN/m^2 generally gave settlement values satisfying the maximum allowable limits for mat foundations on clays, while a bearing pressure of 80kN/m^2 gave excessive settlement values.

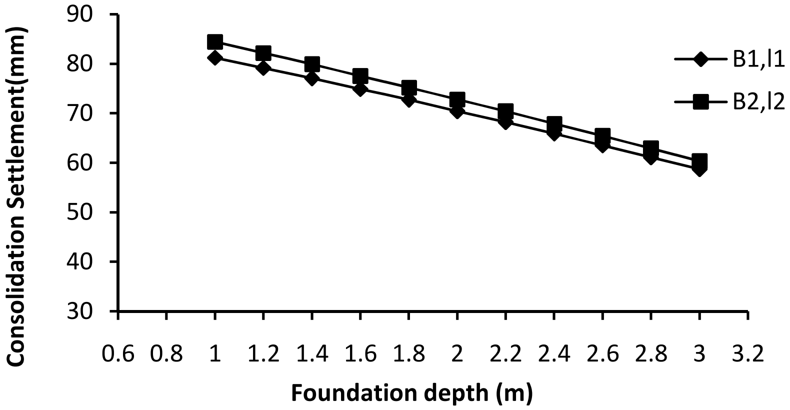

Figure 6: Variation of consolidation settlement with foundation depth for q_n = 50kN/m^2

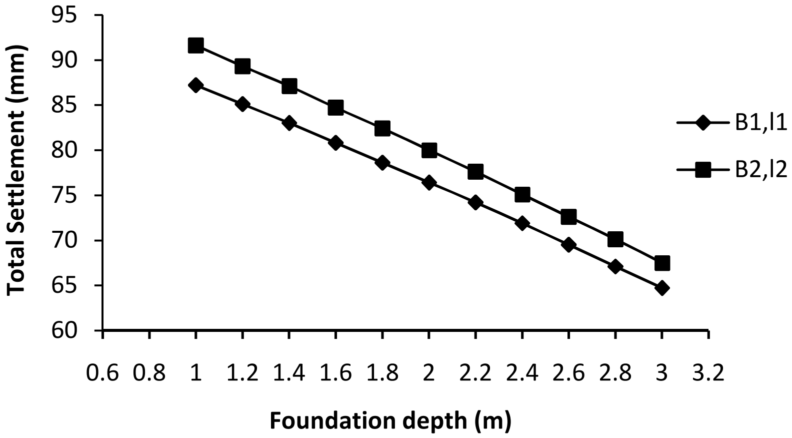

Figure 7: Variation of total settlement with foundation depth for q_n = 50kN/m^2

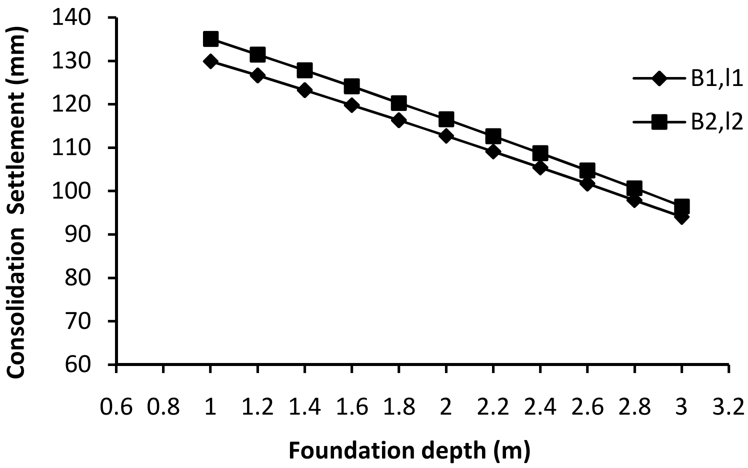

Figure 8: Variation of consolidation settlement with foundation depth for q_n = 80kN/m^2

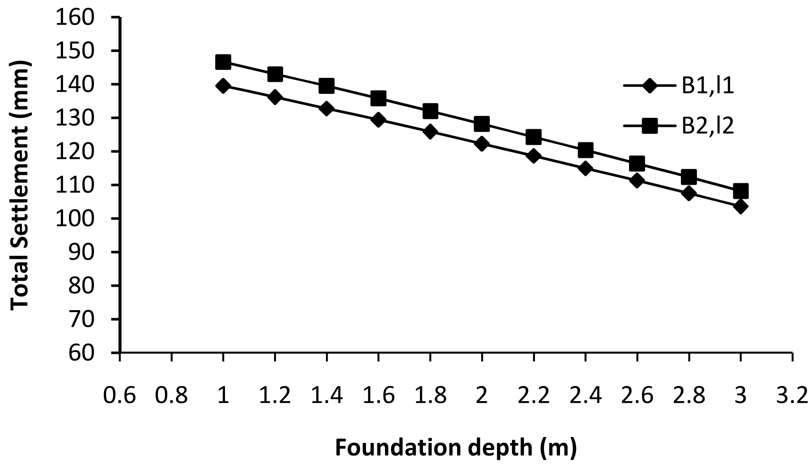

Figure 9: Variation of total settlement with foundation depth for q_n = 80kN/m^2

Table 1: Bearing Capacity

BH No	Depth of Foundation (m)	Unit Weight γ (kN/m^3)	Undrained Cohesion 'c$_u$' (kN/m^2)	Angle of friction ϕ (degrees)	Allowable bearing capacity qa, (kN/m^2)	
					B = 19.3m	B = 23.3m
1	1.0	17.5	32	2	78	79
	1.5	“	“	“	78	79
	1.7	“	“	“	78	79
	2.0	“	“	“	78	79
	2.5	“	“	“	78	79
	3.0	“	30	3	80	81
2	1.0	17.4	31	3	81	82
	1.5	“	“	“	81	82
	1.7	“	“	“	81	82
	2.0	“	“	“	82	83
	2.5	“	“	“	82	83
	3.0	“	30	3	80	81
3	1.0	17.4	32	3	83	84
	1.5	“	“	“	84	85
	1.7	“	“	“	84	85
	2.0	“	“	“	84	85
	2.5	“	“	“	84	85
	3.0	“	30	4	84	86
4	1.0	17.4	30	2	73	73
	1.5	“	“	“	73	74
	1.7	“	“	“	73	74
	2.0	“	“	“	73	74
	2.5	“	“	“	74	74
	3.0	“	“	“	74	74

Table 2: Settlement Analysis of Mat Foundation

Foundation Depth(m)	B_1=19.3mm, L_1=25.2mm $q_{n(a)}$ = 80kN/m^2		B_1=19.3mm, L_1=25.2mm $q_{n(a)}$ = 50kN/m^2		B_2=23.3mm, L_2=29.2mm $q_{n(a)}$ = 80kN/m^2		B_2=23.3mm, L_2=29.2mm $q_{n(a)}$ = 50kN/m^2	
	Consolidation settlement ρ_c (mm)	Total Settlement, ρ_t, (mm)	Consolidation settlement ρ_c (mm)	Total Settlement, ρ_t, (mm)	Consolidation settlement ρ_c (mm)	Total Settlement, ρ_t, (mm)	Consolidation settlement ρ_c (mm)	Total Settlement, ρ_t, (mm)
1.0	129.9	139.5	81.2	87.2	135.0	146.7	84.4	91.6
1.2	126.6	136.2	79.1	85.1	131.4	143.1	82.1	89.3
1.4	123.2	132.8	77.0	83,0	127.8	139.5	79.9	87.1
1.6	119.8	129.4	74.8	80.8	124.1	135.8	77.5	84.7
1.8	116.3	125.9	72.6	78.6	120.3	132.0	75.2	83.4
2.0	112.7	122.3	70.4	76.4	116.5	128.2	72.8	80.0
2.2	109.1	118.7	68.2	74.2	112.6	124.3	70.4	77.6
2.4	105.4	115.0	65.9	71.9	108.7	120.4	67.9	75.1
2.6	101.7	111.3	63.5	69.5	104.7	116.4	65.4	72.6
2.8	97.9	107.5	61.1	67.1	100.7	112.4	62.9	70.1
3.0	94.0	103.6	58.7	64.7	96.5	108.2	60.3	67.5

CONCLUSION

The following conclusions can be drawn from the study;

i. A slight lateral variability in bearing capacity of soil is noticeable in the compressible soil lithology, while variability in bearing capacity values with depth at investigated points is almost reproducible. The variation in foundation dimensions (i.e. B and L) has no significant effect on the allowable bearing capacity.

ii. Induced vertical stress, $\Delta\sigma$, depicts an increasing trend with increase in foundation depth. Larger $\Delta\sigma$ were associated with larger foundation dimension under the same given bearing pressure.

iii. Consolidation settlement on mat foundation was found to decrease with increase in foundation depth and size.

iv. Total settlement decreased with increase in foundation depth and foundation dimension.

v. Evaluated bearing capacity values did not satisfy the maximum allowable settlement requirement for mat foundation on clays.

vi. Mat foundations satisfied both bearing capacity and settlement requirements under a bearing pressure of 50kN/m^2, which is lower than evaluated bearing capacity for the site. Consequently, settlement consideration determined the choice of bearing capacity needed for the foundation analysis and design in Sandy CLAY formation.

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