PRACTICAL CONSIDRASTIONS FOR DIMINISHING PILED RAFTS ON WEAK LAYERED SOILS

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ABSTRACT

Alluvial deposits are abundant in the world especially in coastal areas. Due to their young geological formation, very stiff strata are not normally obtained even at great depth, which maximizes the cost of conventional foundation variants for heavy weight structures. This paper presents basic considerations for optimized design of foundations of high-rise buildings on alluvial soils of the West African coastal city of Lagos by using piled rafts. Soil parameters have been determined from interpretation of extensive soil data from test records of different high-rise building projects within the area and back analysis of static pile load test results. Effects of raft thickness, pile length and spacing on the load-settlement behaviour of piled rafts were studied by employing three-dimensional non-linear Finite-Element Analysis. Normalized curves for practical loads in the area were produced to enhance design of piled rafts for similar conditions. The extensive parametric studies with uniform length piles and uniformly distributed external loads indicated the advantage of having widely spaced piles for reducing the foundation costs. Analysis results of a specific high-rise building in Lagos were found to be in good agreement with the findings of the parametric studies and previous researches with comparable input parameters.

Keywords*:* Piled rafts, back-analysis, weak layered soils, non-linear, 3D Finite Element Analysis

INTRODUCTION

Piled raft is a hybrid foundation system which accounts for the load share of rafts resting on group of piles, which is traditionally ignored in the conventional pile design methods irrespective of the existing interactions between the piles, raft and soil layers. Due to its economic significance, wide ranges of application have been exercised in the last four decades for different soil conditions [1, 2, 3]. Much has not been reported about its suitability on alluvial deposits around coastal areas of younger geological ages [4]. This research has been motivated from the observations of the actual design and construction practice related to structures on such deposits.

Due to the relatively weak subsoil formation in the development-oriented megacity of Lagos [5], it is customary to use very long piles for the foundations of these high-rise buildings to achieve the required capacity to withstand the super-structural loads and the associated settlements [6].

The introduction of this hybrid foundation system of piled raft not only provides economic benefits, but also favours the enhancement of the construction industry by solving the practical difficulties of using very long piles with the introduction of shorter piles to reduce the settlement of the raft which can share a certain portion of the total super-structural load acting on the foundation [7].

The research was carried out by analysing the ground condition in the selected area and preparing the material parameters required for the numerical analysis which employed the commercial Finite Element software package ABAQUS. While an axisymmetric simulation was used to calibrate the parameters from pile load test results with appropriate constitutive model, three-dimensional non-linear analysis was employed for modelling the behaviour of the piled raft foundation system. The load share of the foundation elements and settlement reduction has been studied by varying the length of piles configured in simple and practical arrangements. Pile length staggering is beyond the scope of this research and the load is assumed to be uniformly distributed.

Load -Settlement Behaviours

Resistance of the components

Being a composite foundation system constituting the piles, the raft and surrounding soil, quantifying about the interactions between these components of a piled raft foundation is the basis for its behaviour [8]. The bearing capacity of a piled raft is thus a function of the interactions between these components. By considering the characteristic loads, subscripted as *k* in the following equations, the settlement dependent total resistance of the foundation unit, $R_{tot,k}(s)$ is the sum of the resistances of all individual piles $R_{pile,k,j}(s)$and the raft $R_{Raft,k}(s)$, or equivalently:

$$R_{tot,k}(s) = \sum_{j=1}^{m} R_{pile,k,j}(s) + R_{Raft,k}(s) \qquad (1)$$

The resistance of the individual piles is computed as the sum of the base and skin friction resistances:

$$R_{pile,k,j}(s) = R_{b,k,j}(s) + R_{s,k.j}(s) \qquad (2)$$

The resistance of the raft can be determined by integrating the stress under the raft $\sigma(x, y)$ over the (raft-soil) contact area:

$$R_{Raft,k}(s) = \iint \sigma(x, y)dxdy \qquad (3)$$

The total external load $F_{tot,k}$is carried partly by the piles and partly by the contact pressure between the raft and the soil. The proportion of the load carried by the piles is usually expressed using the pile - raft coefficient,α_{pr}, which is defined as:

$$\alpha_{pr} = \frac{\sum_{j=1}^{m} R_{pile,k,j}(s)}{R_{tot,k}(s)} \qquad (4)$$

The value of pile – raftco efficient depends fully on the allowable settlement. If there is a stringent requirement to limit the settlement within a certain prescribed range, then higher number of piles or longer piles can be used leading to a higher value of the pile-raft coefficient, and vice versa. This can be explained better with the relationship between the pile - raft coefficient and the normalized settlement, defined as the ratio of the settlement of piled raft to that of unpiled raft, ξ_s, shown in Fig. 1, which has been derived from practical cases recorded in the past.

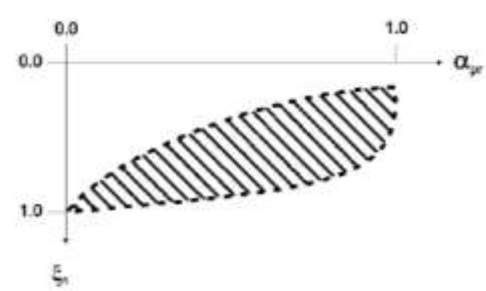


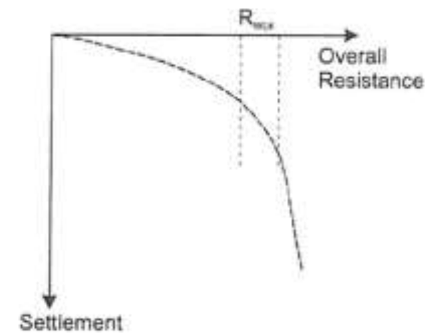
Fig. 1 Relationship between normalized settlement and pile-raft coefficient [4]

Safety provisions of piled rafts

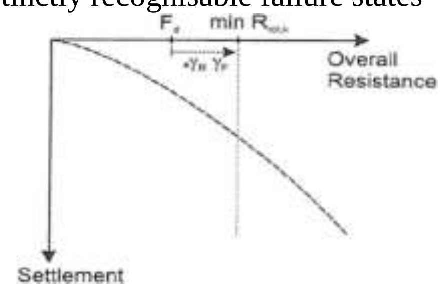
Various research works have been carried out to assess the bearing capacity of piled rafts using theoretical, experimental and numerical tools in different parts of the world [9, 10, 11]. Katzenbach et al. [12] proposed a piled raft design concept based on the provisions of [13]. The overall resistance of piled rafts in ultimate limit state (ULS) $R_{tot,k}$ is defined as the point at which the increase in settlement becomes significantly super-proportional, analogous to single pile resistance, as presented in Fig. 2a. However in most cases of piled rafts the variation of settlements with the resistance is of the form shown in Fig 2b, where a gradual variation of the resistance with settlement is observed. This is due to the enhanced bearing resistance of piled rafts due to favourable interactions within the components. Thus a minimum resistance $min\ R_{tot,k}$ shall be set in such a way that failure of the foundation can be adequately avoided. In both cases the overall resistance shall be greater than the sum of the applied characteristic load $F_{c,k}$, multiplied by the partial safety factors for the load (γ_F) and the resistance (γ_R) .

The use of a partial safety factor of unity for the resistance and two for the characteristic load as suggested in [14] is equivalent to the customary method of applying a single global safety factor of 2. The guideline compiled by Katzenbach and Choudory [15] defines the safety concept both for the ultimate and serviceability limit states by applying appropriate partial safety factors for individual components in the respective cases.

$$R_{tot,k} \geq F_{c,k}\,\gamma_F\,\gamma_R \qquad (5)$$



a) Distinctly recognisable failure states



b) Non distinctly recognisable failure states

Fig. 2 Non-linear system behaviour of a piled raft and determination of the overall resistance [12]

Study Area

The area under investigation lies within the alluvial deposits of South-West Nigeria Basin which is an integral part of Dahomeyan Embayment, which lies to the east of the Dahomey Republic and to the north of the Bight of Benin [16, 17]. The local formation consists of sedimentary deposits of silts sands and clays underlain by recent deposits which vary from the littoral and lagoon sediments to the coastal belt and alluvial deposits of the major rivers [18]. A continuously shifting sedimentation of the clay and sand sediments was also reported by [19, 20].

The engineering soil properties in the study area have been evaluated from extensive field and laboratory investigation results of different high-rise building projects in Victoria Island, which is located in the southern part of Lagos city [4]. Field investigation included more than 19 boreholes with standard penetration tests (SPT) and 47 cone penetration tests (CPT) up to a maximum depth of 63 m. The water table was found within a depth of 3.5 m from the ground surface, and all further computations in this research were carried out by assuming the whole soil to be submerged in water. Based on interpretation of these field investigation results, the multi-layered soil has been idealized to consist of our soil layers as shown in Table 1. Soil parameters for the computational models have not been taken simply from the laboratory test results, due to the reason that laboratory results are generally extremely conservative [21]. Constrained moduli of the soils have thus been determined by employing empirical correlations with the SPT and CPT values in addition to the laboratory Odometer test results, to account for the in-situ conditions. The basic soil parameters summarized in Table 1 are thus obtained by combining the measured values from laboratories with those correlated based on extensive field investigation results. These basic parameters have further been calibrated using the pile load test simulations discussed in the next section.

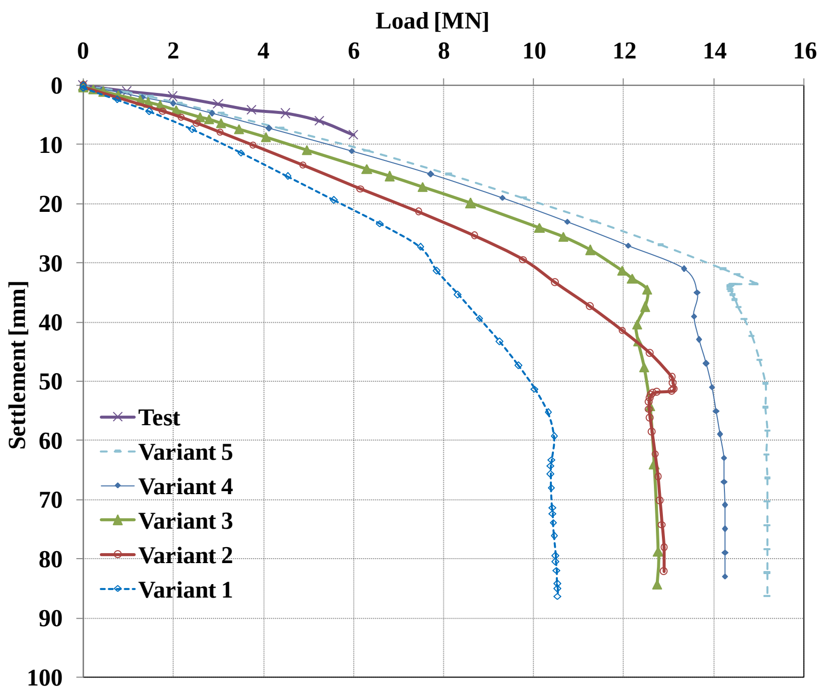
Table 1. Summary of soil parameters determined from field and laboratory investigation results.

Depth [m]	**0 – 10**	**10 – 20**	**20 – 40**	**40 – 63**
Soil layer	Loose sand (SAND1)	Medium dense sand (SAND2)	(Firm clay CLAY)	Dense sand (SAND3)
Standard penetration test N ranges	1- 12	11-22	-	12-57
Cone penetration q_c ranges	0.2-7	0.5-40	0.5-35	-
Young's modullus of Elasticity$E$ [MN/m²]	18 - 24	26-41	5-33	45-70
Effective unit weight γ' [kN/m³]	8.0	8.5	8.0	10.0
Effective angle of friction φ' [^{o}]	29.0	32.2	22.6	34.0
Cohesion c' [kN/m²]	-	-	29.2	-
Poison's Ratio ν [-]	0.3	0.3	0.4	0.3
Static Earth pressure coeff. K_0 [-]	0.52	0.47	0.54	0.44

Calibration of Materials Parameters from Pile Load Test

Since the use of soil parameters representing the in-situ conditions is a key requirement for simulating the real problems, pile test results are recommended for high-rise buildings categorized into the Geotechnical Category GC 3 of the Eurocode EC 7 [13, 15]. Accordingly pile load tests performed within the study area have been used to calibrate the soil parameters based on in-situ conditions.

A working pile of 47 m length and 800 mm diameter, loaded up to a maximum of 6 MN and a corresponding settlement of 8 mm, has been used to investigate its load - settlement behaviour. Since the pile load test was not carried out till failure as shown in Fig. 3, the back analysis has mainly been based on comparison of the initial part of the test result. The axis-symmetric Finite Element analysis using the commercial software ABAQUS considered the cap plasticity constitutive model for the soil and elastic behaviour for the pile. Since the major parameter affecting the load-settlement behaviour is the stiffness of the soil layers, as proven by preliminary sensitivity analysis, different calculation variants were carried out by varying the elasticity modulus of successive layers from the range of values in Table 2. Results of selected computation variants only have been presented in Fig. 3.



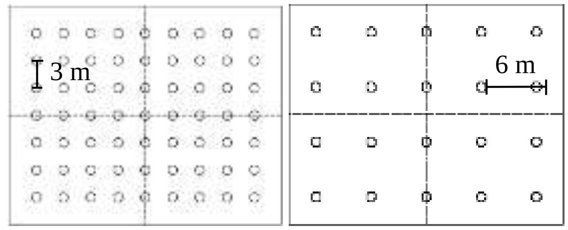
Elasticity [MPa]	SAND 1	SAND 2	CLAY	SAND 3
Variant 1	23	33	8	56
Variant 2	25	40	20	70
Variant 3	**25**	**40**	**35**	**70**
Variant 4	100	100	100	100
Variant 5	100	100	100	200

Fig. 3 Calibration of representative static pile-load test using FEM

The results of Variant 1, where the stiffnesses of the soil layers were taken as the arithmetic mean of the corresponding layers (Table 1), deviatenoticeably from the pile - load test results. Since the test results were found to be about three times stiffer than the simulated results, which is actually in agreement with findings of previous researches [21], the other variants were performed by considering the upper ranges of the soil layer stiffnesses. Variant 3 was performed by considering the values from the upper limit of the range of elasticity shown in Table 1, while variant 2 is used to show the influence of the soil layer where the pile tip rests. Variants 4 and 5 were performed by stiffening all the soil layers beyond the aforementioned ranges of parameters with the aim of approaching the measured values. Since stiffening the soil layers to as much as 4 times the mean value of Variant 1, the required calibration could not have been achieved. Thus Variant 3, which considers the maximum range of elasticities from the mean values and whose results plot mid-way between the results of the test and the FE simulation with that of Variant 1, has been chosen for the remaining research works.

Settlement and Load Sharing Behavior of Piled Rafts on Weak Ground

Application of piled rafts for the ground condition calibrated earlier have been investigated after rigorous parametric studies by varying selected geometric parameters of the foundation units with the location of the pile tip in the various soil layers. The pile diameter of 1 m was held constantin all the variant computations. After preliminary analysis of using various pile configurations, two pile spacing, namely three and six times the diameter of the pile, 3D and 6D, respectively, were considered for further analyses, which allow the group effect of piles without exaggerated difference between the pile loads, except edge piles of the closely spaced arrangement. This is in line with the recommended range of application of piled rafts [22, 23]. For the configurations of pile spresented in Fig. 4, three raft thicknesses (0.5 m, 1.5 m and 2.5 m) were considered, for each of which the pile length was varied between 5 m and 50 m and the raft edge distance was taken as three times the pile diameter, which is known as the simple case [22].



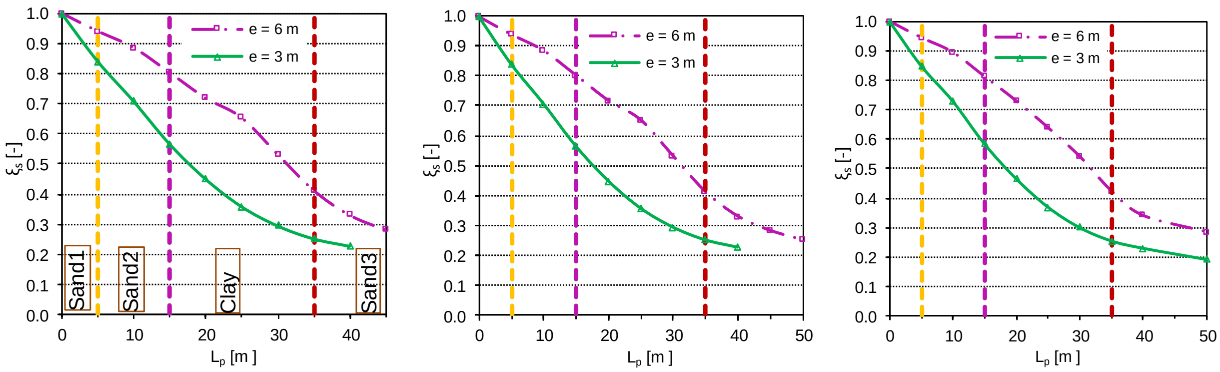
a) e/D = 3 b) e/D = 6

Fig. 4 Pile spacing used for the study

In the 3D-FE computations the successive evolution of the load history has been modeled starting from an initial state in which the primary stresses act on the soil continuum and no construction phases begin. Subsequently installation of the piles follows by removing soil and adding concrete elements as well as excavation of the soil above the raft level by removing the soil within the location of the pit. The raft was then introduced into the foundation system by activating its weight G_{Raft}, as uniformly distributed load over the surface, its stiffness being activated in the subsequent step.

Finally, the super-structural load was gradually added over the surface of the raft till its maximum value.Soil profiles together with their corresponding parameters and constitutive models were adopted from the calibration of the pile-load test.

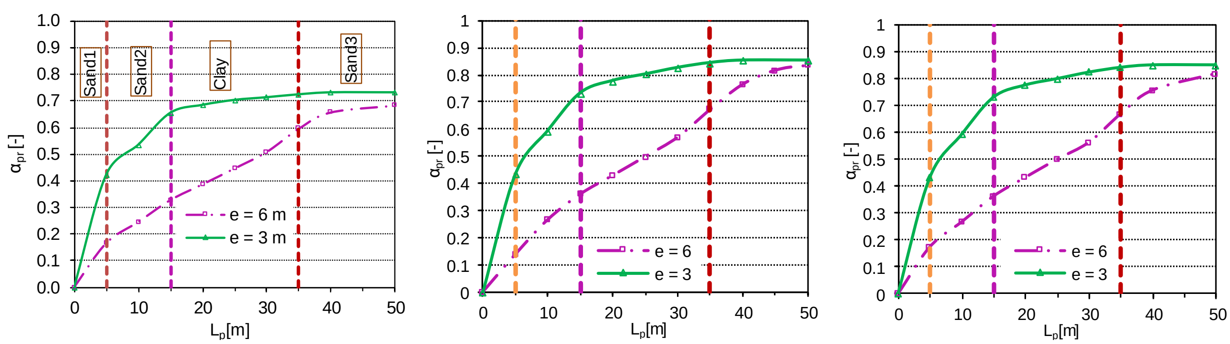
The major findings of these computations, for a uniformly distributed load of 462 kN/m^2, which has been taken from practical loading conditions of high-rise building projects in the area [4], are summarized in Fig. 5 and 6, using plots of normalized settlement ε_s and pile-raft coefficient α_{pr} respectively, as a function of the pile length L_p.



a) t = 0.5 m b) t = 1.5 m c) t = 2.5 m

Fig. 5 Variations of the normalized settlement with geometric parameters of the piles and raft.

The settlement reduction curves show no sudden bend or break at the successive soil layer interfaces except that at the bottom SAND3 layer. Placing the pile tips at this bottom layer, which is twice as stiff as the overlying CLAY layer resulted in very much limited or insignificant reduction instead of further settlement reduction. It is however evident from Fig. 5 that the normalized settlement is found to be affected more significantly by the geometric parameters of the piles. For all the three cases of raft thickness, a limiting pile length is observed, beyond which further pile length increment will not produce settlement reduction, irrespective of the pile spacing. Thus, the wider spacing remains to be economical above the limiting length as far as settlement reduction is concerned. The advantages of the closer spacing in reducing the settlements can only be appreciated when the pile length is well below the limiting length especially with flexible raft. The maximum difference between the two spacings is actually observed at intermediate depth (about 10 – 30 m in this case), though it calls for further investigations in order to determine the optimum value.



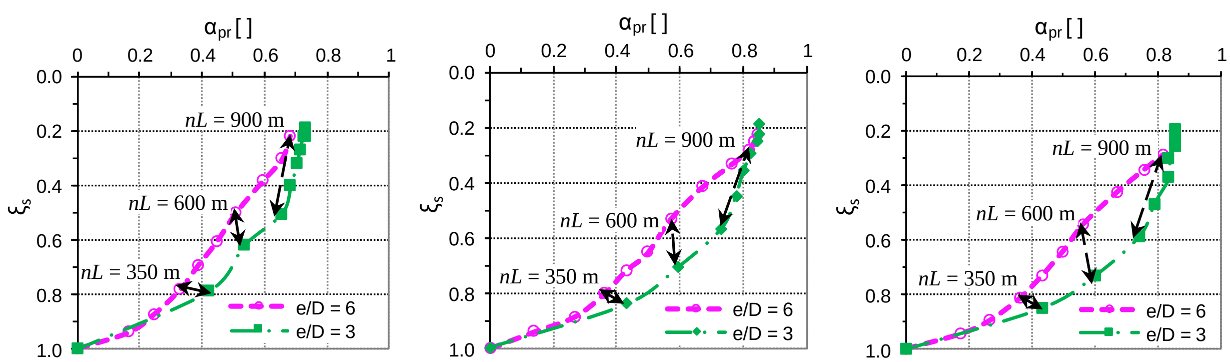
a) t = 0.5 m b) t = 1.5 m c) t = 2.5 m

Fig. 6 Variations of the pile raft coefficient with geometric parameters of the piles and raft.

The dominant factors affecting the pile - raft coefficient are pile spacing and length, in a similar fashion as that of the normalized settlement (Fig. 6). For the ground condition under consideration, with no great variation of the soil stiffness till great depth, the change in layer stiffness of the soil layers as well as raft thickness do not substantially influence the pile-raft coefficient. However, further detailed studies with regard to the effects of soil layering and raft thickness are recommended to come to confirmed conclusions.

The general tendency of reduction of the pile-raft coefficient with increasing pile spacing agrees with previous findings [23], as it might be expected. While the denser pile spacing doesn't favor the contribution of the raft on load sharing except for short piles (up to about 15 m), the raft shares considerable amount of the total load for wide range of investigated pile length (up to about 40 m) in the case of widely spaced piles. This is due to the enhanced pile-raft interaction by wider pile spacing except for exceptionally long piles. Thus, pile length increment has practically no significance on the load share of the foundation elements if excessively long piles are to be used. It is also to be recalled that the use of very long piles with denser pile spacing can only lead to limited settlement reduction without even increasing the pile load share, which was the practice in the study area.

The above results motivate the use of the wider spacing in almost all cases, except for minimizing settlement while using piles of intermediate length. To assist the choice of a better arrangement of the piles to optimize the required outputs, the normalized settlement is plotted against the pile - raft coefficient for the range of raft thickness and pile spacings considered as shown in Fig. 7. The '*total pile meters*', *nL*, calculated as the product of the uniform pile length and the number of piles, is used for a better comparison. Points of equal pile meter in the two configurations are joined using arrow lines in the plots to facilitate interpretation.



a) t = 0.5 m   b) t = 1.5 m   c) t = 2.5 m

Fig. 7 Variation of the normalized settlement with pile-raft coefficient for different geometric conditions

In all the cases, the normalized settlement decreases while using the wider spacing although the difference will be exaggerated when total pile meters increases, due to enhanced stiffness of the ground. On the other hand, the pile raft coefficient remains fairly constant at intermediate pile meters (about *nL* =600 m), while the contribution of the raft is enhanced by smaller pile meters for the wider spacing, and by higher pile meters at closer spacing, though the latter is not significant. For instance, the use of the very close spacing with very large pile meters could only help reduce the pile-raft coefficient by less than 10 %while increasing the settlement as much as twice as that of the widely spaced configuration, which will not be practically desired.

While all the curves plot within the ranges of Fig. 1, indicating the possible applicability of piled rafts in the region, the use of flexible raft as in Fig 7a is characterized by somehow reduced pile - raft coefficient. Quantitative comparison of the results shows that the load share of flexible raft will be higher for both spacings of piles as illustrated in the works of [24] due to increased pile-raft interaction. On the other hand thickening the raft leads to widening the gap between the settlement reduction curves for the two pile spacings.

Widening the pile spacing and reducing the raft thickness contribute to the enhancement of the pile-raft interaction, by decreasing the pile-pile interaction, and hence increasing the load share of the raft. Doubling the pile spacing is thus generally found to enhance the performance of the piled raft, as both normalized parameters are reduced substantially in a very wide range of total pile meters.

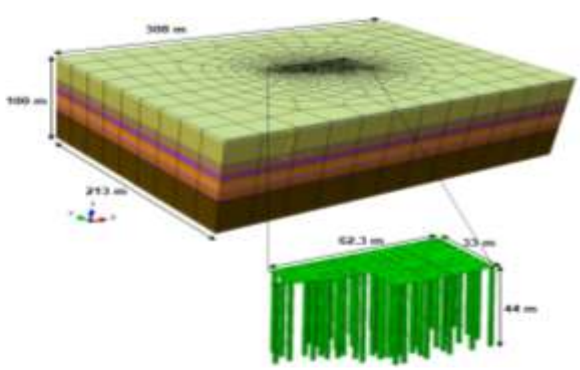


Fig. 7 Geometry of the basic numerical model

Practical Case of Piled Rafts on Layered Deposits of Lagos

The practical applicability of piled rafts in the study area is illustrated by a 75 m high building project with similar loading and material parameters as the case indicated in the previous sections. Even if soil investigation results for the project indicated that the ground condition of the site were found to be similar to the case of the previous sections of this research, further considerations were also made, including Ostergberg cell pile-load tests corresponding to the specific project. The calibration of the parameters using site specific soil investigation and back-analysis of the pile-load tests, which have also been reported by [22], were found to be in conformity with the results shown in Table 1.

A three-dimensional, non-linear analysis has been carried out for assessing the behavior of a piled raft foundation by incorporating the calibrated soil parameters, with due consideration of the irregular geometry of the raft and the different loads from the superstructure. The geometry of the model shown in Fig. 7 was used to idealize the soil continuum with the piled raft at the center. The FE-mesh used in the numerical analysis using the commercial software ABAQUS had 97,775 elements and 95,160 nodes. The stepwise calculation phases were similar to the model in the previous section, except the loading conditions, which were idealized as realistic as possible.

Loads on the foundation were determined based on structural calculations by considering dead and live loads, designated as G and Q respectively. Load combinations representing the serviceability limit states and ultimate limit states conditions mentioned earlier in Section 2.2 of this research.

Correspondingly full dead load and live load including the raft own weight, G_{Raft}, or G + G_{Raft} + Q, was used to represent the behavior at serviceability condition. The resistance at ultimate limit states was also determined using the load combination explained in Section 2.2 of this paper using a global safety factor of 2 suggested by [14].

Settlement prediction on the other hand, was carried out by considering the load combination called 'settlement inducing load' [25], which is defined as the sum of full dead load and one third of the live load ($G + G_{Raft} + Q/3$).

After a series of calculations with different pile configurations, a variant with piles of 30 to 44 m long, arranged in such a way that the total load is fairly distributed among all the piles has been selected as the optimal arrangement.

The controlling parameter was the maximum relative differential settlement calculated as 1:700, which was specified by the structural engineers. Further comparison of the maximum settlement with that of un-piled raft shows that the use of piled raft is advantageous in reducing the settlements by 70 %.

The associated load share of the raft corresponding to this settlement reduction was found to be 20 %, and is within the practical values of 0.3 to 0.9 from previous experience of [22]. The contribution of the raft is not large because the design was restricted with the specified deformation requirement, for which the piles were spaced according to the external loads with non-uniform spacing varying between 1.5D and 4.5D. These results of the present case are in a fair agreement with the plots of Fig. 7b, that the normalized settlement and pile-raft coefficient are almost the same, although the load and pile arrangements are different. Thus, the normalized charts of Fig. 7 can be used as guidelines for preliminary design of piled rafts in the area for the specific loading conditions. Further charts can be produced for other load levels, depending on practical developments in the region.

Load-settlement curves have been generated for selected points on the raft (around corners, core and edge of the raft) and plotted in Fig. 8, to determine the load-settlement behavior of the foundation system. All the load-settlement curves have similar patterns except the stiffer behavior at the left part of the raft (Location 1) due to the relatively smaller loads transferred to it. These curves are under the usual category of piled raft described in section Fig. 2b of this paper, non-distinctly recognizable failure states, showing gradual increment of the settlements with load. The observation of no abrupt increase of the settlements for gradual increment of applied load is also an indicator of the advantages of piled raft, that the foundation system doesn't show sudden failure at an expected ultimate load.

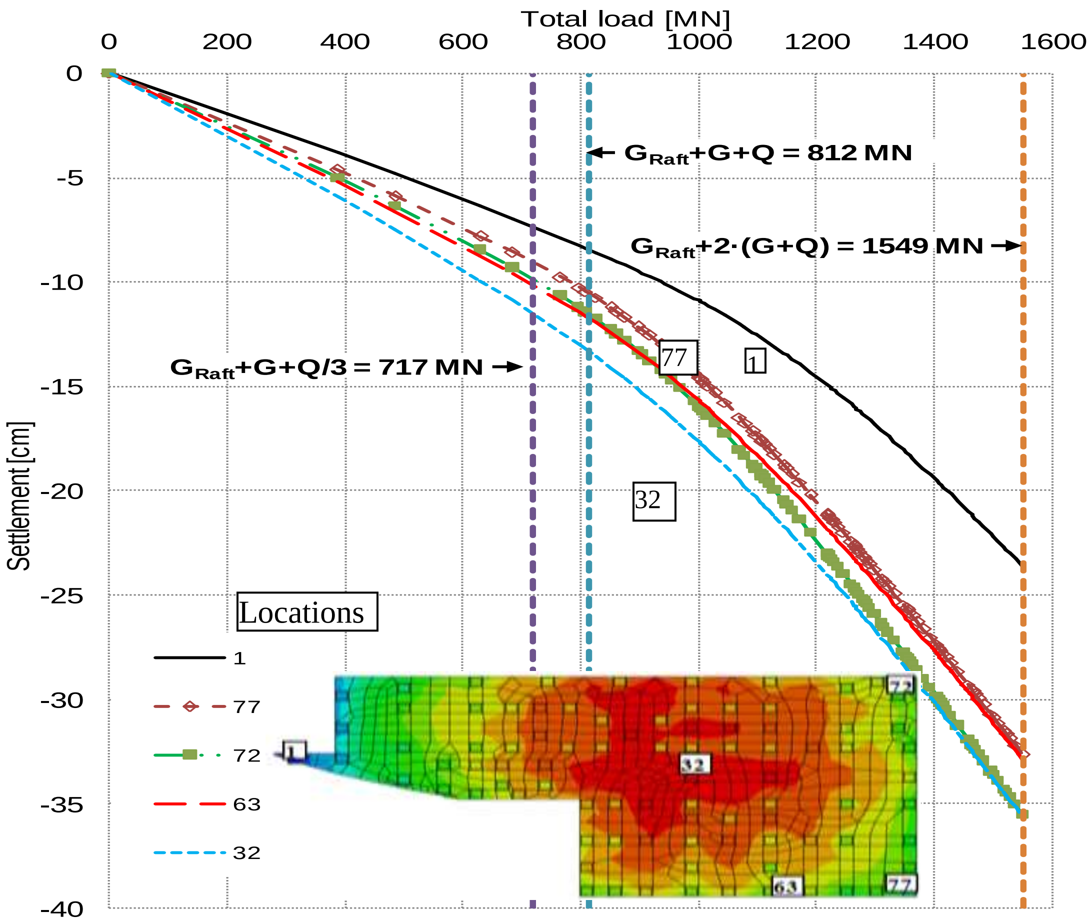


Fig. 8 Load settlement curves at different locations

CONCLUSIONS

This research has focused on the behavior of piled rafts and their applicability on weak alluvial soils of the West African City Lagos, which do not show significant stiffness increment with depth, due to which the use of very long piles is associated with very high project costs. Extensive field and laboratory investigation results have been carefully interpreted and analyzed together with calibration of pile-load test measurements to set the soil parameters incorporated in the non - linear 3D Finite Element Analyses of foundation of multi-story buildings on the stratified alluvial deposits.

Normalized curves of maximum settlement versus pile-raft coefficient for common loading conditions with practical raft thickness ranges indicated the optimal ranges of applicability of piled rafts using two pile spacings, which have been chosen based on findings of previous research works. The common practice of using closely spaced and very long piles have been found to be disadvantageous for both settlement reduction and enhancing the load share of the raft.

The load share of the raft is actually dependent on the specific requirements of the projects regarding the maximum settlement, based on which economical arrangement of the foundation elements can give rise to its best load share. Under the same volume of structural members, the use of widely spaced piles has generally been found to enhance the efficiency of the foundation (reducing both the normalized settlement and the pile-raft coefficient). Economical spacing of the components can thus be considered as smaller pile meters with wider pile spacing, unless the use of higher pile meters is obliged to minimize the settlements, if that is restricted due to the requirements of the specific project.

The practical use of the normalized curves has later been checked by considering a specific site in the region by using piles of smaller length as the traditional practice in the region, which was found to be in good agreement with the general findings of the parametric studies. The load-settlement behavior of the piled raft for the specific site was also observed to have no significant super-proportionality, indicating the absence of sudden failure of the foundation system beyond ultimate loads, which is a characteristic of most piled rafts [12].

The general findings of the research show that piled rafts can be used as optimized foundation options for high-rise buildings on alluvial deposits and other comparable ground conditions which do not show significant increase in stiffness with depth. The use of densely configured long piles has been proved to bring nothing but economical loss, which is recommended to be avoided in the specific study area.

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