International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 12 Issue: 01 | Jan 2025 www.irjet.net p-ISSN: 2395-0072

An Empirical study on Group Pile Settlement Based on Soil Structure Interaction

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Abstract - *Soil is a material of remarkable complexity and heterogeneity, characterized by a strong nonlinear response to external loading. Its behavior depends on coherence properties, saturation, and soil types, which throughout history caused varying constitutive laws designed to explain its behavior properties. An all-inclusive settlement formula for group piles has been developed with consideration of several contributing settlement factors. Such parameters include raft sizes, pile diameters, lengths and spacings, applied vertical pressures, soil modulus, ultimate pile-soil friction, and elastic modulus of the pile. An "influence coefficient" is presented as a way of measuring the influence each parameter has on settlement. The major players in settlement are the applied relatively uniform load, soil modulus, and raft dimensions, while pile diameter, length, and spacing are secondary factors in the mix.*

Key Words: Mohr-Coulomb Model, Finite Element Method, Soil-Structure Interaction, Pile foundation, Friction pile,

1.INTRODUCTION

The structural foundations for buildings serve as the main supporting system for them from above ground level. Most structural elements directly come in contact with the soil in civil engineering. Where the surface soil does not have a sufficient bearing capacity to support the loads of a structure, deep foundations are used to transmit these loads to deeper, stable soil strata. Friction piles rely on frictional resistance developed between the surfaces of the pile against the soil around it, such as stiff clay or sandy soil, to resist loads adequately. The friction may develop along the full length or the toe portion of the pile, depending on soil stratification. Under friction pile systems, the entire surface of the pile will typically be involved in load transfer. Any analysis of settlement, whenever performed, would allow for the determination of stability and performance of pile foundations..

The entire pile group has been assumed to behave as a single entity in the assessment of its behavior, with the summation of base and shaft resistance ultimately determining its capacity. Under close spacing, the overall capacity of a group of piles is therefore more likely to depend on the group performance of the piles rather than that of individual ones. The pile group settlement results from a combination of elastic shortening of the pile and that of the soil supporting it. It is generally assumed that the pile group acts as one deep foundation, like a pier or a mat foundation. Total load on friction piles is, however, assumed to be acting at a depth equal to two-thirds of the pile length. This block assumption is thus likely to overestimate the pile load capacity, rendering precise calculation of the settlement quite difficult. The effects of soil-structure interaction (SSI) can be incorporated into the calculations to improve settlement estimates, while a more advanced formulation for settlement will be derived from the analyses carried out on ANSYS..

Vidhu et al.[1] studied pile settlement behavior and load-carrying capacity at a particular spacing due to variation of the L/d ratio of piles. The study finds that interaction between piles in a group tends to increase more with increasing L/d ratio, resulting in uneven load distribution wherein the outer piles take most of the load, sometimes leading to the initiation of plastic hinges. Also, for a pile group of constant dimensions, settlements under a given load remain almost unvaried over a practical range of spacings. Hence, smaller-diameter piles with larger spacing are preferred from a settlement viewpoint. Jalali et al. [2] studied pile-soil interaction and its effect on pile settlement and shear stress within the interaction zone. Using Mohr-Coulomb and Hard-Soil behavior laws, they found that under loading, the pie displacements were analyzed, where the Static Analysis of PLAXIS gives more reliable measures of settlement when the interface coefficients vary from 0.7 to 1 in the Mohr-Coulomb behavior law as compared to the Hard-Soil model. Shaiana et al. [3] conducted numerical simulations in ABAQUS to investigate pile behavior embedded in cohesionless soil under oblique loads. Comparisons of various analysis procedures were made for single piles under different inclinations. Results suggest that pile stiffness has a strong effect on its behavior under combined vertical and lateral (oblique) loading, where vertical and horizontal load levels are highly dependent on the angle of load inclination (α). The additional horizontal load decreases the ultimate vertical pile capacity of the pile.

Johnson et al. [4] studied 3D finite element modeling to explore how factors like pile shape, sand characteristics, pile length, and loading conditions affect pile capacity. From the trends observed in these simulations, design charts were created to help to calculate the bearing capacity of square piles subjected to oblique loading. A thorough Finite element analysis showed that both sand properties and pile shape have a considerable impact on pile capacity.

2.CREATION OF SETTLEMENT DATABASE FROM FINITE ELEMENT MODELS

Settlement formula is derived from the FE model configurations. The varying model parameters were basically the width (w_{ix}), length (w_{iy}) and thickness (t_h) of the rectangular raft, the diameter (d_i), length (L_e) and spacing of the piles (S_{px} and S_{py}), the applied uniform load (L_d), the soil moduli (E_s) , the ultimate pile-soil friction (f_r), and the elastic modulus of concrete (Ec). The input parameters are shown in Table. 1

The analysis incorporated the Mohr-Coulomb (M-C) soil model, and a parametric study was conducted on its strength parameters, specifically friction angle and cohesion, to assess their relationship with settlement behavior. The findings indicated that these parameters had no direct influence on settlement, which is expected since group pile settlement does not occur in a failure state where soil strength parameters are crucial. Instead, deformations in group pile systems generally remain within the elastic range. Consequently, using a more advanced constitutive model is not considered necessary.

Table -1: The input parameters

No	Description	Symbol	Unit
1	Spacing of piles @ x direction	S_{px}	m
2	Spacing of piles @ y direction	S_{py}	m
3	Length of piles	L_e	m
4	Diameter of piles	d_i	m
5	Width of raft @ x direction	w_{ix}	m
6	Width of raft @ y direction	w_{iy}	m
7	Elastic modulus. of pile concrete	E_c	MPa
8	Soil modulus around piles	E_s	MPa
9	Distributed vertical load	L_d	kN
10	Ult. pile-soil friction	f_r	kN/m
11	Raft thickness	t_h	m

3.GENERAL SOLUTION FOR SETTLEMENT

The settlement dataset obtained from the finite element runs include the values of the settlement at the centre. The derived settlement formula is given as follows:

Settlement

$$S = S_b \cdot \left(\frac{S_{px} \cdot S_{py}}{u_1}\right)^a \cdot \left(\frac{L_e}{u_2}\right)^b \cdot \left(\frac{d_1}{u_3}\right)^c \cdot \left(\frac{w_{ix} \cdot w_{iy}}{u_4}\right)^d \cdot \left(\frac{E_s}{u_5}\right)^e \cdot \left(\frac{L_d}{u_6}\right)^f \cdot \left(\frac{f_r}{u_7}\right)^g \cdot \left(\frac{t_h}{u_8}\right)^h \cdot \left(\frac{E_c}{u_9}\right)^i$$

In this approach, S represents the calculated settlement, while S_B denotes the base settlement in meters. The unitless fitting coefficients a, b, c, d, e, f, g, h, and i are used to refine the settlement formula. A dataset is obtained, consisting of both FE-based and formula-based settlement values, which have not yet been iterated or corrected. To quantify the accuracy of the formula, the squared difference between these two settlement values is computed, defining the “error” for each data point. The total global error is then determined by summing all individual errors. The objective is to minimize this global error by adjusting the unitless coefficients. Using the "Solver" add-on in Excel, these coefficients are iteratively optimized to achieve the best possible fit.

Table – 2: Unitless Fitting Coefficient

a	b	c	d	e	f	g	h	i
-0.16	0.59	0.56	-0.24	0.93	-0.02	0.14	1.00	-0.43

Table -3: Fitting Constants of Settlement Formula with Units.

Constant	Value	Unit
u_1, u_4	1	m^2
u_2 u_3 u_6 u_8	1	m
u_5	1.7	MPa
u_7	13.7	kN/m
u_9	2.7	GPa

A systematic procedure is employed to determine the exponential relationship of each individual input parameter on settlement [5]. In this approach, the influence of a specific parameter is isolated while filtering out the effects of all other parameters. The process begins by selecting a specific finite element (FE) model configuration as the baseline system. Next, variations of this baseline model are created by modifying one input parameter at a time. For each modified configuration, the corresponding settlement is calculated, allowing for a clear assessment of the parameter's independent influence on settlement behavior.

The fitting constants such as u_1, u_4 and u_7 are included in the terms in $(.... + u_n)^n$ format to enhance the fitting (R^2) performance of the formula. Using such a constant like u1 in a term enhances the fitting performance. The fitting constants such as u_{11}, u_{12} and u_{15} are used to normalize the term they are associated to. In addition, the R^2 value of the formula is not affected from normalization. The elastic modulus of soil can be calculated as equivalent elastic modulus of all the soil layer. For large foundations the pressure bulb extents deep into the subsoil hence the estimation of equivalent E_s for various soil layer into which the pressure bulb extends into is needed, the normal practice is to use a weighted average of the modulus of elasticity of the various layers encountered within the depth of influence

$$E_s = \frac{\sum H_i E_i}{\sum H_i}$$

where, E_s =Equivalent modulus of elasticity

H_i = Thickness of layer

E_i = Modulus of elasticity of layer

This method of obtaining equivalent modulus of elasticity is acceptable as long as the variation of individual layers is comparable.

Substituting all the constants value to the general equation.

$$S = S_b \cdot \left(\frac{S_{px} \cdot S_{py}}{1}\right)^{-0.16} \cdot \left(\frac{L_e}{1}\right)^{0.59} \cdot \left(\frac{d_1}{1}\right)^{0.56} \cdot \left(\frac{w_{ix} \cdot w_{iy}}{1}\right)^{-0.24} \cdot \left(\frac{E_s}{1.7}\right)^{0.93} \cdot \left(\frac{L_d}{1}\right)^{-0.02} \cdot \left(\frac{f_r}{13.7}\right)^{0.14} \cdot \left(\frac{t_h}{1}\right)^{1} \cdot \left(\frac{E_c}{2.7}\right)^{-0.43}$$

4. CONCLUSIONS

This paper introduces a general group pile settlement formula that considers the effects of various parameters on settlement. The formula incorporates parameters such as the dimensions of a rectangular raft, pile diameter, length, spacing, applied vertical uniform pressure, soil moduli, ultimate pile-soil friction, and the elastic modulus of the pile. An "influence coefficient" is introduced to quantify the contribution of each parameter. The most crucial factors affecting the settlement are applied uniform load, soil modulus, and raft dimension, while the pile diameter, length, and spacing have moderate effects.

Based on all these observations, it can therefore be concluded that the behavior of a pile group in cohesive soils is influenced by pile length and diameter, soil properties, the spacing of pile groups, soil properties, loading conditions, as well as cost-effective and safe design. That is, an actual site of soil-structure interaction should find its way to the analysis and be considered therein.

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