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Laterally Loaded Pile in Cohesionless Soil

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Abstract—Pile foundations are extensively used to support various structures built on loose/soft soils, where shallow foundations would undergo excessive settlements or have low bearing capacity. Piles are usually slender, having high length to width ratio, and are mainly designed to resist axial loads. However, some structures such as high rise buildings, offshore structure (Quay, harbors), earth retaining walls are also subjected to horizontal or lateral pressure caused by wind force, wave force, traffic movement, water pressure and earth quake. Lateral soil movements mostly have a negative effect on the behaviour of axially loaded piles. Many different methods of analysis have been proposed to solve the problem of a laterally loaded pile, where the problem can be generally defined as computing pile deflection and bending moment as a function of depth below the ground surface. In this thesis work a laterally loaded pile in cohesionless soil whose field test data's available is taken. The pile is modeled in finite element software Plaxis, both in 2D and 3D and the results obtained are compared with the published test results. Also, the analysis is done with Brom's method and Characteristic load method, and the results are compared for validating the program. Then we adopt piles with different characteristics and different soil conditions in-order to investigate the effect of variation of pile and soil properties on behaviour of laterally loaded piles.

Keywords—pile foundation; lateral loads; cohesionless soil

I. INTRODUCTION

Piles are commonly used to transfer vertical forces, arising primarily from gravity. Examples of structures where piles are commonly used as foundations are tall buildings, bridges, offshore platforms, defense structures, dams and dock structures, transmission towers, earth retaining structures, wharfs and jetties. However, in all these structures, it is not only the axial force that the piles carry; often the piles are subjected to lateral forces and moments. In fact, there are some structures where the primary function of piles is to transfer lateral loads to the ground. Wind gusts are the most common cause of lateral force (and/or moment) that a pile has to support. The other major cause of lateral force is seismic activity. The horizontal shaking of the ground during earthquakes generates lateral forces that the piles have to withstand. Certain buildings are also acted upon by lateral earth pressures, which transmit lateral forces to the foundations. That apart, depending on the type of structure a pile supports, there can be different causes of lateral forces.

In this thesis work laterally loaded piles in cohesionless soil whose field test data's available is taken. Laterally loaded pile in cohesionless soil selected here is connected with a navigation project at Arkansas River (USA). In 1970 Mansur & Hunter and Alizadeh & Davisson reported the results of lateral load tests for a number of piles in connection with a navigation project. One of the tested piles is selected here and is analysed. This selected pile is analysed with four different methods, among which two are classical methods and finite element approach. The pile is modeled in finite element software Plaxis, both in 2D and 3D and the results obtained are compared with the published test results. Also, the analysis is done with Brom's method and Characteristic load method, and the results are compared for validating the program. Then we adopt piles with different characteristics and different soil conditions in-order to investigate the effect of variation of pile and soil properties on behaviour of laterally loaded pile.

II. PILE IN COHESIONLESS SOIL

A. Field Test Data

In 1970 Mansur et al. reported the results of lateral load tests for a number of piles in connection with a navigation project. One among these piles is selected for the present study. The pile selected for the study is a steel pile of diameter 406 mm and length of 15 m which is embedded in cohesionless soil. The soil mainly consists of fine sands with some organic silt.

The steel pipe pile had a length of 15 m, diameter of 406 mm and a wall thickness of 8.153 mm is taken. The effective width of the pile was 480.3 mm, the moment of inertia, I_p, was $3.494x10^{-4}$ m^4 and the bending stiffness was 69900 kNm^2. Estimating the yield strength of the steel to be $248x10^3$ kP, yield moment becomes 361 kNm.

Several borings were made to determine the soil parameters. They showed a considerable variation of soil properties around the site. The soil in the top 5.5 m was poorly graded sand with some gravel and little to no fines. The deeper soils were fine sands with some organic silt. The water table was at a depth of 0.3 m. The total unit weight above the water table was $20kN/m^3$ and below it was $10.2kN/m^3$. Data from the site showed that the site had been preconsolidated by an overburden of 6 meters that was removed prior to testing. The reported soil data is given in Table I.

Table I Soil data for Arkansas River

DEPTH FROM G.L. (m)	σ_v (Mpa)	N_{spt}	q_c (Mpa)	σ_v/ q_c	ϕ(degree)	E_s (Mpa)	n_E
0	0	12	5	_	_	15	4
0.6	0.021	12	5	417	45	15	4
2.4	0.039	14	5.5	183	42	15	4
4	0.056	20	10	179	42	22.5	3
4.6	0.062	17	8	129	41	19.5	3
5	0.071	25	13	183	42	27	3
7	0.086	28	14	163	42	28.5	3
8.5	0.102	18	12	118	40	19.5	3
10	0.117	27	15	128	41	30	2.5
11.6	0.133	29	15	113	40	30	2.5
20	0.219	29	15	68	36	30	2.5

The loading was static and was applied at the ground line. Loads of 46, 92, 140, 191, 248 kN were applied at the tip of the pile. To apply the measuring equipment four steel bars were welded to the sides of the pile. The additional steel bars influenced the bending stiffness and width of the pile. The instrumentation of the pile was installed in steel bars that were connected to the pile. This indicated that the occurring moment along the pile. The pile head deflection, y_h, along the x-direction was measured.

The results are given in graphical form, Figure I.

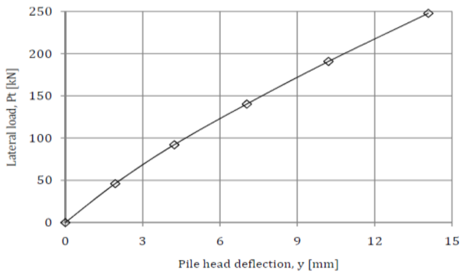

Figure 2.1 Pile head deflection vs. load

B. Validation of the Program

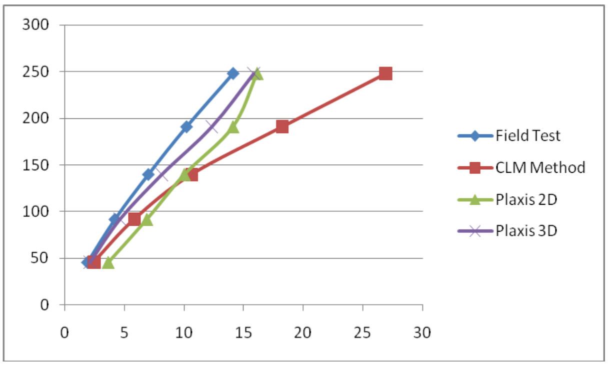

Figure 2.2 Result obtained with different methods compared to the measured for cohesionless soils

Compared with the different methods adopted for the analysis Plaxis gives much better results. Of the two considered models, Plaxis 3D model is more accurate than the 2D model. According to the Broms theory the deflections can be calculated only if the load is between 0.3 to 0.5 times the ultimate resistances. Also it can be used only for homogeneous soils. According to this method the bending stiffness is independent of moment also it is not considering the difference of the bending stiffness over the height of pile. So this cannot be used for more complicated structures. The CLM method adopted is only applicable for long piles and also the influence of pile diameter on soil reaction is not considered. According to this method the bending stiffness is independent of moment also it is not considering the difference of the bending stiffness over the height of pile. This method overestimated the deformations. Because of these limitations the CLM method is not accurate. Plaxis software gives the most accurate results compared with the different methods adopted. Plaxis 3D is a three dimensional program and therefore multiple external effects can be taken into account. So the Plaxis 3D model can be used if the situation is more complicated. However, there are several disadvantages for Plaxis like the model is difficult to compare with other models with different soil conditions. The amount of input parameters are large sp the time necessary to setup the model takes a lot of time. Even though Plaxis may be used, if the situation is very complicated and enough soil data is present.

III. EFFECT OF VARIATION OF PILE AND SOIL PROPERTIES ON BEHAVIOUR OF LATERALLY LOADED PILE

The pile response was analyzed by varying the pile length. The length of the pile is varied from 5 to 15m to include both short pile and long flexible pile behavior. Pile head is assumed to be free headed. Young's modulus of the pile material is considered as 2.74 x10^7 kN/m^2 in the present study which corresponds to M30 grade concrete and pile radius is considered as 0.25 m. A horizontal load of 100.0 kN is applied at the top of the pile. The pile top is assumed to be 1.0 m above ground level and hence an equivalent moment of 100.0 kNm is considered in the analysis. The subgrade reactions are considered as per the inputs provided in Table shown.

The relative stiffness factors for these soil types [$T = (EI/\eta_h)^{0.20}$] are 2.004 (loose sand, dry), 1.61 (medium sand, dry), 1.33 (dense sand, dry) and non-dimensional depth coefficient Zmax varies from 2.49, 3.09 and 3.75 for loose sand, medium sand and dense sand respectively. When the pile length is considered as 5.0 m, the response for a range of soil types viz., loose sand, medium sand, and dense sand is anaysed and the results are presented for pile deflections. It is observed the pile tends to behave as rigid pile under loose sand showing rigid body rotation. However under medium and dense sand condition the flexible type behavior was observed. Lateral pile load analysis based on subgrade reaction approach by Reese and Matlock (1956) theory predicts short rigid pile behavior for Zmax <=2.0. Thus the results are in agreement with Reese and Matlock (1956). Also it can be observed that when the soil stiffness increases the pile deflections are reduced. The pile response is also evaluated considering submerged soil condition and the pile deflections are also presented. It was observed that the pile undergoes higher deflections under submerged condition compared to dry state.

Table II Subgrade reaction considered

η_h (kN/m^3)					
Dry soil			**Submerged soil**		
Loose sand	Medium sand	Dense sand	Loose sand	Medium sand	Dense sand
2600.0	7700.0	20000.0	1500.0	5200.0	12500.0

When the pile length is increased to 10.0m, Zmax varies from 5.0 to 7.5 and hence the pile no more behaves as rigid. The same is observed from the analysis results and the pile deflections are presented in Figure for various soil types under both dry and submerged condition. Also it can be seen from this figure that the stiffness of the surrounding soil has significant influence on the pile response.

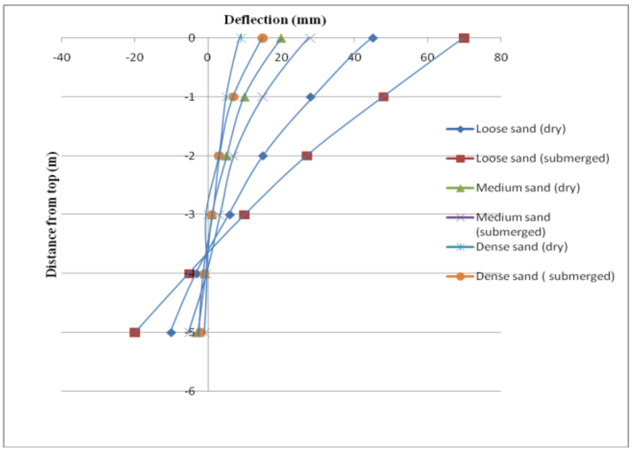

Figure 3.1 Pile deflection along depth (L = 5.0m; r = 0.25m)

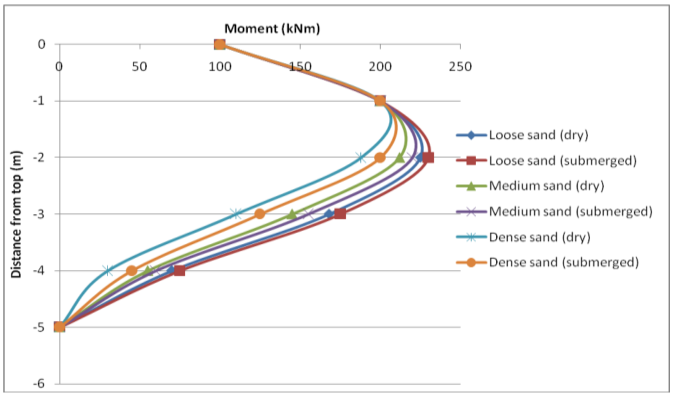

Figure 3.2 Variation of bending moment along depth (L = 5.0m; r = 0.25m)

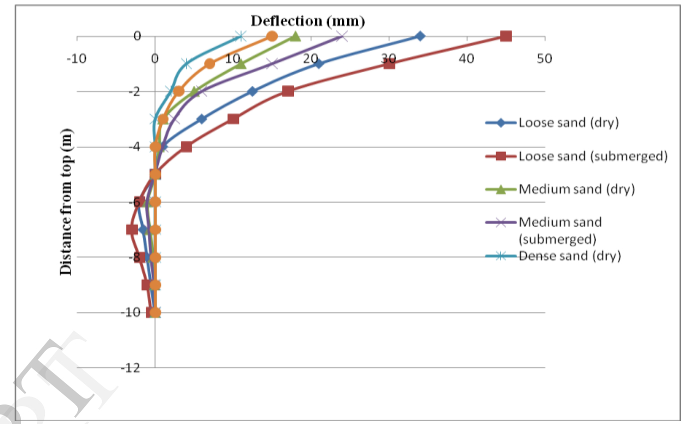

Figure 3.3 Pile deflection along depth (L = 10.0m; r = 0.25m)

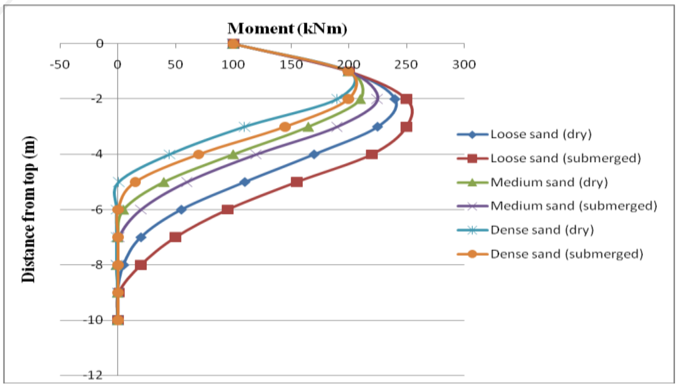

Figure 3.4 Variation of bending moment along depth (L = 10.0m; r = 0.25m)

The analysis is also performed for pile length of 15.0 m for both dry and submerged conditions and it is observed that the pile response is not affected by increase in length anymore which is consistent with Reese and Matlock (1956). Reese and Matlock (1956) theory also shows that the pile response is not affected in the case of flexible piles where non-dimensional depth coefficient Zmax > 5.0.

In the present study, response of single piles in cohesionless soils is evaluated for a given horizontal load and moment. The subgrade modulus for loose sand, medium sand and dense sand based on Tezaghi (1955) are considered both in dry condition as well as in submerged condition for the present analysis. Young’s modulus is considered as 2.74x10^7 kN/m^2 and the pile radius is taken as 0.25m.

Clearly it can be seen that the deflections are reduced as the soil stiffness increases. It was observed that in case of 5.0m pile under loose sand the deflection is increased by about 60% under submerged condition. The increase in medium sand and dense sand in submerged condition was about 35% and 33% respectively for the same pile length. However when the pile length is considered as 10.0m, the pile deflections under submerged conditions are increased by 35%, 28% and 26% respectively for loose sand, medium sand and dense sand. It can be seen that the pile deflections are higher in case of 5m pile length compared to higher length piles. This is due to short rigid behavior of the pile resulting in pile rotations. Also it’s observed that the pile response is not affected by increasing the length of the pile beyond 10m. This is due to the fact that the depth coefficient exceeds 5 and the pile behaves as flexible beyond 10m.

IV. CONCLUSION

Geotechnical software packages, mass-spring models and finite element analyses, are more complete and more accurate models than manual methods or classical methods. Broms and the Characteristic Load Method are not appropriate models to design laterally loaded piles. The methods are unpractical and inaccurate. Compared with these methods Plaxis gives much better results. Of the two considered models, Plaxis 3D model is more accurate than the 2D model. Plaxis is a three dimensional program and therefore multiple external effects can be taken into account. Plaxis may be used, if the situation is very complicated and enough soil data is present.

The lateral load analysis results of single piles in cohesionless soils for range of soils is presented. Both dry condition and submerged conditions are accounted. The effect of pile length, type of soil under both dry and submerged condition, on the deflections was discussed. The study captures both the short pile and long pile behaviour. For short rigid piles, about 60% increase in deflections was observed for loose sands from dry state to submerged condition. The increase in deflections for medium sand and dense sand in submerged condition with respect to dry state are about 35% and 33% respectively. However for flexible piles, the pile deflections under submerged conditions are increased by 35%, 28% and 26% respectively for loose sand, medium sand and dense sand from that of dry soil condition. It was also observed that the pile response is increased by about 5 times in loose sand compared to dense sand under dry condition where as in submerged condition the pile response is amplified by about 4.66 times in loose sand compared to dense sand for short rigid piles. For flexible piles the response in loose sand is amplified by about 3.09 times from the dense state considering dry state and the amplification is about 3 times in submerged condition for loose sands with respect to dense sands.

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