A comparative study of ordinary piles and superlong piles in consolidating soil

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Abstract. This paper presents finite element analyses of negative skin friction on a short single pile, long pile and superlong pile under various conditions. Negative skin friction is a most common problem in designed and construction of pile in a highly compressible soft soil. In this paper, a 3D-dimensional axisymmetric model is built in the finite element program, ABAQUS6.14. The model first is verified with a centrifuge test results. The study concluded that the neutral plane is located closer to the end of the pile as the end bearing increases. Based on the analyses, it is found that the location of the neutral plane is significantly influenced by the pile tip location from bearing layer. the normalized neutral plane decreases with the increase of the pile length embedded in the clay layer. Closed form equations of Shong, 2002, predict the numerical results in well agreement.

1. Introduction

Piles are divided according to length to diameter (L/D) ratio into two types ordinary Piles and superlong piles. The ordinary pile is defined as the pile with length not bigger than 30. The super-long pile is defined as the pile with length not less than 50 m or aspect radius ratio not less than 50. As of late, superlong pile has been widely used in the construction of harbors and high-rise buildings (Xin et al. 2005; Wang and Ma 2005; Zhong et al. 2005). Pile foundations are installed in different soil stratification. Usually the penetrated soil stratifications offer considerable resistance for the pile shaft deformation upon loading. This resistance is called shaft resistance or skin friction. (Briaud 2010) pointed out situations where downdrag force should be considered in the design. The negative skin friction will be mobilized in the upper portion starting from the pile head to a neutral depth, NP, after which positive skin friction is mobilized in the lower portion. Neutral plane (NP) can also be defined as the depth at which the relative displacement between the pile and the soil is zero (Fellenius 2004, and 2006).

Fellenius (2006) presented the results of long-term measurements in driven piles in different sites. Field measurements showed that the negative skin friction and positive shaft resistance developed along piles were governed by the effective stress and were fully mobilized with a very small movement of the pile. Lee et al. (2002 and 2004) developed 2D and 3D finite element FEM models...
using ABAQUS software to investigate the group effects on the distribution of dragloads in pile foundations. Although a serious number of numerical analysis have been carried out to investigate the behaviour of piles subjected to negative skin friction under dragload without considering the effect axial loads on pile (Abdrabbo, et al.2015; Leung et al. 2004; Lam et al. 2013).

Lv et. al. (2016) conducted two centrifugal model tests on a single floating pile to investigate the geometrical effects on axially loaded floating piles subjected to negative skin friction and also to study the response of Y-shaped pile and a circular pile on load transfer mechanisms at Pile length. The authors also carried out the 3D analysis of the centrifuge model tests. The study revealed that the dragload developed along Y-shaped pile is 2.5 times bigger than the circular pile.

Shong, (2002) described a closed form equation for tackling the analysis of negative skin friction. The equations are based on the force equilibrium, and rigid-plastic soil model. That is the distribution of the skin friction discontinue at the neutral plane. Skin friction coefficient is assumed equal for both the positive skin friction and negative skin fiction. According to this approach, the depth of neutral plane, \( L_{NP} \), of pile penetration length, \( L_p \), is:

\[
L_{NP} = \frac{Q_u}{2Q_s \left[ \frac{1 - \frac{Q_d}{Q_u}}{Q_u} \right]^{1/2}}
\]

Where;

\( Q_u \) = ultimate pile capacity = \( Q_s + Q_t \) (2)

\( Q_s \), the pile shaft resistance over the whole shaft length, is:

\[
Q_s = \int_0^{L_p} \beta (\pi D) \sigma_z \, dz
\]

\( L_p \) = length of the pile,

\( D \) = pile diameter,

\( Q_t \), the pile toe resistance:

\[
Q_t = N_t A_t \sigma_z \mid_{z=L_p}
\]

\( A_t \) = the toe area of the pile,

\( Q_d \) = imposed load at pile top

Shong (2002) reported that in case clay a range of \( \beta \) varies between 0.25 to 0.35, and \( N_t \) varies between 3 to 10. In this analysis, the factor of safety of pile capacity Against ultimate pile capacity (\( Q_d/Q_u \)) is considered 2, \( \beta \) is chosen 0.25, and \( N_t \) is taken 3 in case floating pile \((Y=0.25D)\). While in case end bearing pile \((Y=0.00D)\) \( \beta \) is chosen 0.25, and \( N_t =5 \).

The main objectives of the work presented are to investigate the effects of the pile tip conditions on the distribution of negative skin frictions developed along single short pile, long pile and superlong pile embedded in soft clay soil.

2. Numerical modelling

2.1. Pile Geometry, Finite Element Mesh, and Boundary and Initial Condition

Three-dimensional nonlinear axis symmetric finite element (FEM) analyses using ABAQUS6.14 are used for a single pile based on a reported centrifuge test Lv et.al. (2016). The pile is assumed to be embedded in perfect contact with surrounding soil. The three-dimensional element meshes and prototype modelling are shown in Figure 1. 3D, 8-noded pore pressure element C3D8P are used to emulate the soil. Three-dimensional, 8-noded stress with reduced integration elements C3D8R are used to simulate the piles. Because of different embedment length of piles, different tip locations the number of elements and nodes are different. Detailed information on the elements and nodes of the three pile-soil systems are summarized in Table1. Because of the symmetry of the model, only a quarter of the whole finite element mesh is used. The boundary conditions roller supports are set at the
lateral boundary and pinned supports are assigned at the bottom boundary. The drainage boundary pore pressure \(u = 0\) kPa is specified at the top clay surface. A limiting relative shear displacement \((\gamma_{crit})\) of 5 mm is considered adequate enough to achieve a full mobilisation of shear strength along pile shaft. Once the relative shear movement at pile-soil interface came to \((\gamma_{crit})\) the tangent shear stiffness \(\tau\) at the pile soil interface becomes zero. Interface friction angle, \(\delta\), was adopted as proposed by (Randolph and Worth 1981, Lv et al. 2016). There for, the interface friction coefficient of 0.32 is used in these analyses. The limiting relative shear displacement is taken as 0.005 m.

### Table 1. A Summary of the elements and nodes in the numerical analyses

| Case            | Tip location (Y) | Number of elements | Number of nodes |
|-----------------|------------------|--------------------|-----------------|
|                 |                  | Pile | Soil | Pile | Soil |
| Short pile      | 1.00D            | 2880 | 9216 | 3721 | 11377 |
|                 | 0.25D            | 2880 | 9216 | 3721 | 11377 |
|                 | 0.00D            | 2880 | 26160 | 3721 | 30624 |
| Long pile       | 1.00D            | 2880 | 19776 | 3721 | 24217 |
|                 | 0.25D            | 2880 | 20224 | 3721 | 24749 |
|                 | 0.00D            | 2880 | 25104 | 3721 | 29408 |
| Super long pile | 1.00D            | 9600 | 19296 | 12261 | 24047 |
|                 | 0.25D            | 4800 | 11776 | 6161 | 14617 |
|                 | 0.00D            | 4800 | 10880 | 6161 | 13553 |

**Figure 1.** Finite element meshes adopted for (a) quarter three-dimensional meshes; (b) fined elements at pile–soil interface; (c) quarter whole model section; (d) quarter circular pile section.
2.2. Constitutive Models and Parameters

To simulate the stress path of soil experienced in centrifuge tests correctly, the prototype model is used in numerical back-analyses. The constitutive models and parameters for each solid are shown in Table 2. The soil properties refer to the work of Lv et. al. (2016). In Table 2, \( M \) is the slope of the critical state line, in \( q-p' \) space, \( k \) slope of normal consolidation line, \( k \) slope of swelling line, under isotropic compression of clay, and \( p'_o \) is the value of \( p' \) at the intersection of the yield locality with the \( p' \) axis. The soil is consisted by two layers, including 12 m sand underneath 18 m clay. The bottom sand is modelled as an elastoplastic material. Top clay is modelled as Cam-Clay model, while pile model as liner elastic model.

**Table 2.** Constitutive Models and Material Parameters Adopted for Numerical Analyses (after Lv et. al.2016)

| Properties                                      | pile            | Bottom sand   | clay      |
|------------------------------------------------|-----------------|---------------|-----------|
| Constative model                               | Liner-elastic   | Mohr-Coulomb  | Cam-Clay  |
| Unit weight \( \gamma_{sat} \) (kN/m\(^3\))    | 27              | 19.4          | 16.3      |
| Poisson’s ratio of soil \( \nu \)               | 0.35            | 0.30          | 0.35      |
| Modulus of elasticity \( E' \) (kN/m\(^2\))     | \( 1 \times 10^7 \) | \( 1.2 \times 10^5 \) | -         |
| \( M \)                                        | -               | -             | 0.98      |
| \( \lambda \)                                   | -               | -             | 0.14      |
| \( k \)                                        | -               | -             | 0.012     |
| \( p'_{o} \) (kN/m\(^2\))                      | -               | -             | 64        |
| The initial void ratio \( e_o \)                | -               | 0.73          | 1.6       |
| Friction angele at the critical state \( \phi' \) | -               | 29.7\(^{\circ}\) | 25\(^{\circ}\) |
| Angel of dilation \( \psi \)                    | -               | 8.3\(^{\circ}\) | 0\(^{\circ}\) |
| \( k_o = (1-sin\phi') \)                        | -               | 0.50          | 0.58      |
| Coefficient of permeability \( k \) (m/s)        | -               | \( 1 \times 10^{-4} \) | \( 1 \times 10^{-8} \) |

2.3. Verification of the numerical modelling

Figure 2 shows the comparison between numerical and experimental distribution of shear stress and dragload along circular single pile. The figure which also presents the measured values by Lv et. al. (2016), for circular pile, revealed good correlation between present study and laboratory test results. The general agreement between FEM results and field measurements demonstrates that 3-D FEM model can be used to study negative skin friction on a single pile.

2.4. 3D FEM model for parametric study

The verification model Lv et. al. (2016) is modified to investigate the change in the distribution of negative frictions developed along short piles, long piles and superlong piles respectively. In this study, the coefficient of over consolidation ratio (OCR) for the clay layer is taken 1.2 furthermore, in
In this study, a series of finite element analysis of concrete single piles was carried out by studying the influence of the location of the pile tip on the behaviour of short piles, long piles and super long piles embedded in consolidated clay under surcharge load as shown in Figure 3. In this analysis, to reveal the influence of the tip location, parametric studies are carried out on two floating piles with $Y = 1.00D$ and $0.25D$ and one bearing pile with $Y = 0.00D$ in all cases: short piles, long piles and super long piles, respectively. The parameters study is shown in Table 3.

**Figure 2.** Comparison between FEM and measured data (a) Shear-stress distributions along the pile surface and; (b) Dragload distribution for a single circular pile

**Figure 3.** Subsurface profile and pile embedment’s (parametric study)
Table 3. Influence factors used in parametric analysis.

| Model study | Case            | \(L_p\) (m) | Diameter of pile (m) | OCR | \(P'\) (Kpa) | \(Y\) (m) | \(H_c\) | \(H_s\) |
|-------------|----------------|-------------|---------------------|-----|---------------|-----------|---------|---------|
| Short pile  | floating       | 16.8        | 1.2                 | 1.2 | OCR × \(\sigma\) | 1.00D     | 18      | 12      |
|             | end bearing    |             |                     |     | 0.025D        | 17.1      | 12.9    |         |
|             |                |             |                     |     | 0.00D         | 16.8      | 13.2    |         |
| Long pile   | floating       | 30          | 1.2                 | 1.2 | OCR × \(\sigma'\) | 1.00D     | 31.2    | 12      |
|             | end bearing    |             |                     |     | 0.025D        | 30.3      | 12.9    |         |
|             |                |             |                     |     | 0.00D         | 30        | 13.2    |         |
| Superlong pile | floating   | 50          | 1.2                 | 1.2 | OCR × \(\sigma\) | 1.00D     | 51.2    | 12      |
|             | end bearing    |             |                     |     | 0.025D        | 50.3      | 12.9    |         |
|             |                |             |                     |     | 0.00D         | 50        | 13.2    |         |

\(L_p\) Embedded length of pile  
\(H_c\) Depth of clay layer  
\(H_s\) Depth of bottom sand layer  
\(\sigma\) Vertical effective stress

3. Single pile behaviour

3.1. Effects of the tip location on piles subjected to a surcharge Load

Figures. 4(a), 3(b), (3c), (3d), (e), and (f) show the changes disruptions of shear stress and dragload for short piles, long piles and superlong piles respectively at different pile tip locations. As shown in Figure 3, pile tip location ranged from 0.25D (end bearing pile) to (0.25D-1.00D) floating pile. As can be seen from the figure, the dragload developed along the pile increases with the decreases of distance \((Y)\) between pile tip and bearing layer. Dragload increases until it reaches a peak value at an intermediate depth. Then, it decreases. Dragload decrease reflects a decrease in the negative skin frictions developed along the pile shaft. That is the developing of positive shear stress along the pile shaft. Hence, the zone of the peak dragload is a transition zone from negative skin friction to positive skin friction. Obviously, the neutral plan is located at this peak point. Shear stress starts from zero value at the surface of the soil and increases until it reaches a peak negative value at an intermediate depth, then it decreases down to zero at the elevation of the neutral plane where the positive skin friction develops. On the other hand, can be seen from Figure 3, the magnitudes and locations of both dragloads and negative skin frictions developed along short pile, long pile and superlong pile increases with the decreases of distance between pile tip and bearing layer. Neutral plane is determined where shear stress changes from negative to positive. That is at the intersection of the curve with the vertical axis. As can be seen from the Figure the location of the neutral plane is matched from these two approaches. As can be seen from Figure, the transition zone of superlong piles is located near to the middle of the pile. The transition zone of short pile is located near the pile toe. The neutral plane is located at the peak point of the transition zone. In addition, it can be seen that the normalized neutral depth is 0.71, 0.8 and 0.95 for short pile at different cases of pile tip locations, \((Y=1.00D, Y=0.025D,\) and \(Y=0.00D)\) respectively. The normalized neutral plane is 0.70, 0.73 and 0.77 at the same pile tip locations in long pile. While the normalized neutral plane is 0.69, 0.7and 0.73 for superlong pile at the same pile tip locations. That is the neutral plane is located closer to the end of the pile tip as the base layer gets stiffer. This observation can be explained based on the simple equilibrium of vertical forces. (Accumulative negative skin friction = accumulative positive skin friction + bearing resistance). Since small-bearing resistance is available for floating pile, positive skin friction should be large enough to resist negative skin friction. Hence, negative skin friction will be reduced with the neutral plane being located further from the pile tip and vice versa.
3.2. Effect of the pile length embedded in the clay layer on the location of neutral plane

Figure 5 illustrates the normalized neutral depth as a function to the pile length embedded in the clay layer. The pile diameter is 1.2m. Three cases, Y=0.25D, Y=0.25D and Y=0.00D of tested piles are shown in the Figure. As can be seen from the Figure, the normalized neutral depth decreases with the increase of the pile length embedded in the clay layer. The explanation of the effect of the pile length on the neutral plane is due to the compressibility of the pile length. When negative skin friction is induced in a short pile, most of the downdrag is transmitted to the pile tip in the form of penetration to the bearing layer. Whereas, for superlong pile and long pile the downdrag is partly taken by the pile compressibility, and partly transmitted to the tip.
3.3. Calculation of the neutral Plan

Shong approach is adapted to calculate depth of the neutral plan. The factor of safety of pile capacity against ultimate pile capacity, $F_s$ is considered 2, and $\beta$ is taken 0.25, and $N_t$ is taken=3 in case floating pile ($Y=0.25D$) and $N_t = 5$ in case end bearing pile ($Y=0.00D$) respectively. Figure 6 depicts the normalized neutral depth from both the numerical results data and Shong approach. The pile diameter is 1.2m. three cases short pile, long pile and superlong pile are shown in the Figure. As can be seen from the Figure, the calculated normalized neutral depth is almost having the same trend as the computed ones. The approach results into good agreement with the normalized neutral depth.

4. Conclusion

This paper presents a study on the behavior of short pile, long pile and superlong pile during soil consolidation. This paper presents a numerical investigation of NSF in a single short pile, long pile and superlong pile under various influencing factors, including the tip pile locations on the distribution
of negative skin friction along shaft of pile embedded in consolidating soil. It is found that the neutral plane changes significantly with the tip pile location for bearing layer and pile length. The neutral plane is located closer to the end of the pile as the base layer getting stiffer. The normalized neutral depth increases with the increase of the pile length. Shong approach for neutral plane results into good agreement with the computed ones.

References

[1] ABAQUS 6.14 [Computer software]. 2017. Providence, RI, SIMULIA.
[2] Abdrabbo, F. M., & Ali, N. A. (2015). Behaviour of single pile in consolidating soil. Alexandria Engineering Journal, 54(3), 481–495.
[3] Briaud J. L. 2010. Designing for downdrag on uncoated and coated piles. Piling and Deep Foundation. Middle East.
[4] Bozozuk M. 1972. Downdrag measurements on a 160-ft floating pipe test pile in marine clay. Canadian Geotechnique J. 9(2), 127-136.
[5] Fellenius B. H. 2004, Unified design of piled foundations with emphasis on settlement analysis. ASCE. Geotechnical Special Publication. GSP 125, 253 - 275. Fellenius B. H. 2006. Piled foundation design clarification of a confusion. Geotechnical News Magazine. 24 (3), 53-55.
[6] Fellenius B. H. 2006. Piled foundation design – clarification of a confusion. Geotechnical News Magazine. 24 (3), 53-55.
[7] Lam, S.Y., Ng, C.W.W., Leung, C.F., and Chan, S.H. 2013. Shielding piles from downdrag in consolidating ground. J. Geotech. Geoenviron. Eng., 139(6), 956–968. doi: 10.1061/(ASCE)GT.1943-5606.0000764.
[8] Lv, Y.R., Ng, C.W.W., Lam S.Y., Liu H.L, and Ding, X.M. 2016. Comparative study of Y-shaped and circular floating piles in consolidating clay. Can. Geotech. J., 53:1–12. doi: org/10.1139/cgj-2015-0634.
[9] Lee, C.J., Bolton, M.D., Al Tabbaa, A. 2002. Numerical modelling of group effects on the distribution of dragloads in pile foundations. Geotechnique 52(5), 325–335.
[10] Lee, C.J., Ng, W.W. 2004. Development of downdrag on piles and pile groups in consolidating soil. J. Geotech. Geoenviron. Eng. 130(9), 905–914.
[11] Leung C. F., B. K. Liao, and Chow Y.K. 2004. Behavior of pile subject to negative skin friction and axial load. Japanese Geotechnical society.44 (6), 17-26.
[12] Randolph, M. F., and Wroth, C. P. (1981). “Application of the failure state in undrained simple shear to the shaft capacity of driven piles.” Géotechnique, 31(1), 143–157.
[13] Wang, T. and Ma, Y. (2005). “Study on over-length drilled pile bearing behavior under vertical load.” Rock Soil Mech., 26(7), 1053–1057.
[14] Xin, G. F., Zhang, Z. M., Xia, T. D. (2005). “Experimental study on the bearing behaviors of over length piles under heavy load.” Chin. J. Rock Mech. Eng., 24(13), 2397–2402.
[15] Zhong, W. H., Shi, M. L., Liu, S. Y. (2005). “Load transfer performance of overlength piles.” Rock Soil Mech., 26(2), 307–318.