Study on the key parameters and settlement regularities for flexible- piled composite foundation

Wanfeng, Liu¹, Yongdong Yang¹², Yuanfang lv¹
¹College of Civil Engineering, LongDong University, QingYang, GanSu, 745000, China
²College of Geology Engineering and Geomatics, Chang’an University, Xi’an, ShanXi, 710054, China

Abstract. The flexible-piled composite foundation is one of common processing ways to treat with soft subgrade. The parameters are discussed to improve the accuracy of settlement deformation calculation. Soil deformation parameters and misuses of settlement calculation parameters are analyzed by the theory method and finite element method (FEM). Based on the mechanism of deformation of lime-soil piles, the relationship between stress and strain of pile and soil is analyzed. Meanwhile, calculating key parameters of effective pile length, composite modulus and additional stress are proposed by the theory method. At last an engineering example is described to explain their application.

1. Introduction

The flexible pile is the pile which modulus and strength are relative to smaller than the traditional reinforced concrete pile, but its elastic modulus and strength is larger than the surrounding soil. The flexible pile foundation is subjected to the interaction of pile and soil. The upper load is borne by the pile and the surrounding soil. The deep-mixing pile, lime pile, extrusion foundation by usually soil piles and lime-soil compaction piles are common using in the engineering in the eastern Gansu in China. Lime-soil composite foundation is used in collapsible loess areas. By the construction process, the surrounding soil is compacted and decreasing the collapsible.

For the composite foundation, settlement computation of the piles is as important as bearing capacity when the consolidated foundation is designed. By the analysis of the composite modulus of rigid piles, flexible-piled and semi-rigid piled composite foundation according to the technical standard for ground treatment of building (JGJ79-2012). (Abdrabbo & Gaaver, 2012; Ai & Feng, 2014; Banerjee, 1978;) discussed and identified the application conditions and united calculating method of the code formula, and proposed the new method for composite foundation which had been proved by an application case. By considering the load-deformation characteristics of the pile shaft separately from those of the pile base, (Bourgeois, De Buhan, & Hassen, 2012; Chow, 1986; Ding, Zhang, Li, & Cheng, 2016;) derived the formulas of settlement of single pile. Fayyazi, Taiebat, & Finn (2016) promoted the deformation calculation formulas in condition of deep excavations by analyzing the effect of pile-soil interaction and settlement induced by deep excavation. Gu et el (2008) educed the foundation sedimentation formula of grouting pile based on the balance relation of force and displacement coordination conditions by elastic theory and divided the soil into reinforcement area and lower underlying layer and established the sedimentation calculation model. Based on the vertical point solution of multilayered elastic medium, (Gazetas, Fan, & Kaynia, 1993; Ghasemzadeh & Alibeikloo, 2011; Ilyas, Leung, Chow, & Budi, 2004; Kong & Zhang, 2004; K. M. Lee & Xiao, 2001;) presented a
method of the elastic analysis of axially loaded single pile in multilayered soil by the results of the model test. Load tests were carried out on the following: an isolated single pile, single-loaded center piles in groups, foundation without any piling, free standing pile groups, and piled foundation. The influences of pile driving and the inter-actions among bearing components on load-settlement and load transfer characteristics of piles and the bearing behavior of a cap in a group are investigated separately by comparing their respective test results. (S.H. Lee & Chung, 2005; McVay, Zhang, Molnit, & Lai, 1998; Ng, Zhang, & Nip, 2001; Ottaviani, 1975; Papadopoulou & Comodromos, 2010) thought that the compression layer of composite foundation was consisted of three aspects: the first layer was from the ground to effective length of pile, the second one was from bottom of effective length of pile to top of lower underlying layer and the third was lower underlying layer. (Randolph & Wroth, 1979; Mark. F. Randolph & Wroth, 1978; Salgado, Tehrani, & Prezzi, 2014;) established an approximate closed form solution of a vertically loaded pile in the linear elastic soil and derived numerical techniques to give the load-settlement ratio of the piles in terms of the pile geometry and stiffness.

To sum it, there are three patterns for settlement calculation of the composite foundation. (1) The sections are graded by stress-ratio method to pile or the soil layers and summing the settlement of each section. (2) The compression layer is divided into reinforced and non-reinforced areas, calculating the settlement respectively and summing it. (3) The compression layer is divided into three parts: the effective pile length areas, reinforced areas and non-reinforced areas. The critical pile length is introduced. Composite foundation has been widely applied in the civil engineering, but its study on settlement is relatively fall behind in the engineering practice. Settlement of composite foundation is especially important when treating deep soft foundation, so it is quite necessary to study on settlement calculation. Based on the known research findings, research on settlement of composite foundation has been carried out in this paper.

2. Formulation of the problem

2.1. Effective pile length (lₑ)

The effective pile length can be defined from load and deformation when pile is subjected to the external loads. The foundation bearing capacity is hardly changed when the pile is increasing greater than criticality length, and the length is defined as effective pile length. With the pile length increasing, the relative base deformation becomes little. Its means that the pile length has the nonlinear effect on the base deformation, and it can be ignored. According to analyze the effective length, a FEM (finite element model) model is established by Ansys 14.5(fig.1). In this model, the soil and the pile are both considered as D-P material. For reducing running time, the model choose 1/2 section. The pile and soil are choosing Solid65 element. The target surface on contact surface chooses Target170 and the contact areas chooses conta173. The left and right surface enforce constraints x=0. The behind surface enforces constraints y = 0 and the bottom of the basement enforce constraints x=y=z=0. The diameter of the pile chooses 400mm, and the length of the pile is 8m. The area force acting on the top of the pile is 360kPa. The solution shows that the settlement of the pile is decreasing along the pile. The maximum displacement arises the top of the pile. From the figure, the pile deformation mutations appear near the pile bottom, its length is 6.6m.

Use the same method, choosing the diameter of the pile is 400mm, and choose different pile length(1.5m, 3m, 4.5m, 6m, 7.5m, 9m,12m,15m) in the model. According post-processing, obtain the displacement of the top of the pile with different length. Then the slope of the settlement of the relative displacement of the different length of the pile is calculated. And to get the curve between pile length-diameter ratio and the relative slope of settlement curve of pile top (fig.2). According to the figure, with the pile length-diameter ratio increasing, the relative settlement of the pile becomes small. And the relative settlement holds the line parallel to the x-axis. And the effective length (lₑ) is defined the length at the point of the inflection the curve. Dai Guoliang, et. (2012) proposed the location of the effective length is where the increasing rate of pile stiffness equals to zero. And the effective length can be
described: \( l_c = 1.5 \left( \frac{E_p A_p}{k} \right)^{1/2} \), in which, \( E_p \) is represent the modulus of elasticity of the pile and \( A_p \) is the cross-section areas of the pile. \( k \) means the spring stiffness of pile side soil. Qin Jianqing (2000) obtain the formula of the effective length of soil cement composite foundation by the study on the deformation of soil cement composite, \( l_c = 1.5D \left( \frac{E_p}{E_s} \right)^{1/2} \left( \frac{3\lambda(1 + \mu)}{\lambda + 2} \right)^{1/2} \), in which \( D \), \( E_p \), \( E_s \) means the pile diameter, modulus of elasticity and the elasticity modulus of pile side soil. And \( \lambda \) is the slope value of the affected zone when the pile deformation appears. \( \mu \) is the poisson ratio of the soil.

Figure 1. The displacement cloud figure of the composite foundation (d=400mm, L=8m)

Figure 2. The curve between pile length-diameter ratio and the relative slope of settlement curve

Sun linna (2006) derived the formula of flexible effective length by analyzing the settlement regularity of the deep mixing pile composite foundation, and the formula is \( l_c = (4.1 - 4.5)r_0 \left( \frac{E_p}{E_s} \right)^{1/2} \), in which \( r_0 \) is the radius of pile. Considering the construction, the third formula is used in the paper for the better usability and convenience.

2.2. The composite modules (\( E_c \))

Piles and interactive soil are all elastic. And the load of the foundation is bared by the pile and soil base with the deformations consistency. And we can get the formulation.

\[
P = mP_p + (1 - m)P_s
\]

Where, \( P_p \) denotes the pile bearing loads, and \( P_s \) denotes the base bearing.

\[
E_c = mE_p + (1 - m)E_s
\]

The equilibrium equation of a single pile embedded in the soil modeled using the load transfer or modulus of subgrade reaction method is given by

\[
E_p A_p \frac{\partial^2 w}{\partial z^2} - kw = 0
\]

in which \( E_p \) means Young’s modulus of the pile material; \( A_p \) means cross-sectional area of pile; \( w \) means axial deformation; \( z \) means depth co-ordinate and \( k \) means modulus of subgrade reaction of soil in units of force/length².

And we obtain

\[
w(z) = C_1 e^{bz} + C_2 e^{-bz}
\]

In which \( b = \left( \frac{k}{E_p A_p} \right)^{1/2} \)

When \( z = 0, w(0) = P_p \cdot A_p \)

\( z = l, w(l) = n \cdot P_p \cdot A_p \)

According to relation of the load and deformation \( P_p = E_p b \lambda \), where \( \lambda = \frac{1 + \xi \tanh \beta}{\xi + \tanh \beta} \), \( \beta = bl \)
and \( \xi = \frac{k_2}{E_P A_P} \), \( k_z = \frac{Q_b(1-\mu)}{4\pi r_b G_b} \).

Then we get the formula
\[
E_c = mkhE_p + (1 - m)E_s
\] (5)

2.3. Additional stress of the foundation

The additional stress of the foundation is the stress which is directly emerged from the upper loader. The additional stress at any point in the foundation is produced by the load of pile and pile side soil.
\[
\sigma_z = \sigma_{zp} + \sigma_{zs}
\] (6)

In which, \( \sigma_{zp} \) is the additional stress which is produced by the load acting on pile. And \( \sigma_{zs} \) is produced by the load acting on pile side soil. Mindlin(1936) promoted a solution of the three dimensional elasticity equations for a homogeneous isotropic solid a concentrated force acting in the interior of a semi-infinite solid. If the force is acted the position \( c \) under the ground.
\[
\sigma_z = \frac{p}{8\pi(1-\mu)} \left\{ -\frac{(1-2\mu)(z-c)}{R_1^2} + \frac{(1-2\mu)(z-c)}{R_2^2} - \frac{(z-c)^3}{2R_1^2} \right\}
\] (7)

Where \( R_1 = (x^2 + y^2 + (z - c)^2)^{1/2} \) and \( R_2 = (x^2 + y^2 + (z + c)^2)^{1/2} \). \( x, y, z \) refer to the force acting point from horizontal, orientation and vertical distance. \( \mu \) refers to the poisson ratio, \( c \) refers to the distance under the ground.

3. Settlement calculations

3.1. Deformation in the range of effective length

In the range of the effective length, the load is mainly bared by the pile. And the pile compression at any length can be calculated by the integral equation.
\[
s_{11} = \int_0^{l_c} \frac{p_p(z)}{E_p(z,p)} \, dz
\] (8)

In which, \( p_p(z) \) is the expression of pile stress along pile. \( E_p(z,p) \) is the elasticity of the pile. Integrate it, can be obtained formula(9).
\[
s_{11} = \frac{4p_b l_c}{9E_p}
\] (9)

3.2. Deformation in the reinforced area

Soil in the consolidating layer is homogenous. Compression is one-dimensional. Soil properties are constants. In the reinforced area, the pile and the pile side soil is combined action and satisfied the deflections consistency. In this area, pile and soil can be as a whole, and use the composite modulus to calculate the deformation. The formula (10) can be obtained.
\[
s_{12} = \frac{p_{lc} + p_l}{2E_c} (l - l_c)
\] (10)

Where, \( p_{lc} \) refers to the additional stress when the depth \( z = l_c \); \( p_l \) refers to the additional stress when the depth \( z = 1 \); And \( E_c \) refers to the composite flexible modulus of the foundation.

3.3. Deformation in the subjacent bed

Additional stress is key parameter to calculate deformation in the subjacent bed. It can be used Mindlin-Boussinesq methods to solve the deformation.
\[
s_2 = \sum_{i=1}^{n} \frac{p_i + p_{i-1}}{2E_{si}} H_i
\] (11)

Where \( p_i \) refers to the additional stress of the \( i_{th} \) soil layer; \( p_{i-1} \) refers to the additional stress of the \( (i-1)_{th} \) soil layer; and \( E_{si} \) refers to the elastic modulus of \( i_{th} \) soil layer.
4. Optimal design with the settlement of composite foundation

As the base treatment project an example in Huachi county in QingYang city, Gansu Province in China, the soil layer is divided into 4 parts. And the main physics and mechanics characteristic of the layers is given into table 1.

| material | Mean height (m) | Elastic modulus (MPa) | Density (kg/m³) | Poission ratio | Cohesion (kPa) | friction angle(°) |
|----------|-----------------|-----------------------|-----------------|---------------|---------------|------------------|
| 1st layer | 1.7             | 7.0                   | 1800.0          | 0.40          | 30.0          | 21.6             |
| 2nd layer | 11.3            | 7.0                   | 1770.0          | 0.40          | 38.6          | 18.1             |
| 3rd layer | 5.5             | 20.0                  | 1770.0          | 0.30          | 34.5          | 25.3             |
| 4th layer | 10.0            | 8.0                   | 1800.0          | 0.35          | 45.2          | 23.4             |
| pile      | 18.0            | 110.0                 | 1720.0          | 0.30          | 520.0         | 38.4             |

In this project the treatment methods of the foundation is lime-soil pile composite foundation. The upper loader is 600kPa, and the design pile diameter is 400mm and the design pile length is 18m, and the pile is deposited by lime-soil. And the lime-soil mass ratio is 12%. According to the data of the geological content, the composite modulus is 25MPa, and the soil in unreinforced parts is 9.6MPa. According to the parameters of the composite foundation and the formulas above, the 18m length pile is calculate. The pile elastic modulus is \( E_p = \frac{110MPa.l_c = 14.7m} {1} \). The total settlement, the settlement of reinforced area and nonreinforced area are obtained (table.2), and compared with the realistic data. We can find that the proposed method is closed with the realistic method. Yet the FEM method is larger than the data. So the proposed methods in this paper is available.

| reinforced area (mm) | nonreinforced area (mm) | Total settlement (mm) |
|----------------------|-------------------------|-----------------------|
| FEM                  |                         | 19.52                 |
| PM                   | 1.90                    | 10.80                 | 12.70                 |
| RM                   |                         |                       | 13.88                 |

*PM means the method which proposed in the text.
*RM means data from the field test.

5. Conclusions

Based on the upper bound of limit analysis, a method is presented to calculate the basement settlement. According to the local geological content, the settlement of the flexible composite pile can be calculated. According to the FEM analysis, with the pile length-diameter ratio increasing, the displacement of pile top is decreasing. And the deformation of the surface of soil foundation is changing with the pile deformation. However, with the increasing the pile length cannot be effective improving bearing capacity. The pile length can be designing as effective length. Secondly, deformation of the pile sticking into cushion and underlying layer soil could be deduced by solving the equations which is hardly obtain by the field tests. Finally, an example indicated that the analytical method which was presented in this paper could better reflect settlement characteristics of pile–soil composite ground.

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References

[1] Industry standard of the People’s Republic of China. (2012) Technical code for ground treatment of
[2] Abdabobo, F. M., Gavre, K. E. (2012) Simplified analysis of laterally loaded pile groups, Alexandria Engineering J., 51: 121–127.

[3] Zhiyong, A., Dongliang, F. (2014) BEM analysis of laterally loaded pile groups in multi-layered transversely isotropic soils, Engineering Analysis with Boundary Elements. J., 44: 143–151.

[4] Banerjee, P. K. (1978) Analysis of axially and laterally loaded pile groups. Developments in Soil Mechanics. J., 1: 317–346.

[5] Bourgeois, E., De Buhan, P., and Hassen, G. (2012) Settlement analysis of piled-raft foundations by means of a multi-phase model accounting for soil-pile interactions. Computers and Geotechnics. J., 46: 26–38

[6] Chow, Y. K. (1986) Analysis of vertically loaded pile groups. International Journal for Numerical and Analytical Methods in Geomechanics. J., 10: 59–72

[7] Xuanming, D., Ting, Z., Ping, L., Ke, C. (2016) A theoretical analysis of the bearing performance of vertically loaded large-diameter pipe pile groups. Journal of Ocean University of China, 15: 57–68.

[8] Fayyazi, M. S., Taiebat, M., Finn, W. D. D. L. (2014) Group reduction factors for analysis of laterally loaded pile groups. Canadian Geotechnical J., 51: 758–769.

[9] Gazetas, G., Ke, F., Kaynia, A. (1993) Dynamic response of pile groups with different configurations. Soil Dyn. Soil Dynamics and Earthquake Engineering. J., 12: 239–257

[10] Ghasemzadeh, H., Alibeikloo, M. (2011) Pile-soil-pile interaction in pile groups with batter piles under dynamic loads. Soil Dynamics and Earthquake Engineering. J., 31: 1159–1170.

[11] Ilyas, T., Leung, C. F., Chow, Y. K., Budi, S. S. (2014) Centrifuge Model Study of Laterally Loaded Pile Groups in Clay. Geotechnical and Geoenvironmental Engineering. J., 130: 274–283.

[12] Linggang, K., Liming, Z. (2004) Lateral or torsional failure modes in vertically loaded defective pile groups. Geo-Support. J., 1: 1–12, 2004.

[13] K.M.L., Z. R.X. (2001) A simplified nonlinear approach for pile group settlement analysis in multilayered soils. Canadian Geotechnical J., 38: 1063–1080

[14] Su-Hyung, L., Choong-Ki, C. (2005) An experimental study of the interaction of vertically loaded pile groups in sand. Canadian Geotechnical J., 42: 1485–1493.

[15] Michael, M., Limin, Z., Thomas, M., Peter, L. (1998) Centrifuge Testing of Large Laterally Loaded Pile Groups in Sands. Journal of Geotechnical and Geoenvironmental Engineering. 124: 1016–1026.

[16] Charles W. W. N., Limin, Z., Dora, N. (2001) Response of Laterally Loaded Large-Diameter Bored Pile Groups. Journal of Geotechnical and Geoenvironmental Engineering. 127: 658–669.

[17] Ottaviani, M. (1975) Three-dimensional finite element analysis of vertically loaded pile groups. Géotechnique. J., 25: 159–174.

[18] Papadopoulou, M. C., Comodromos, E. M. (2010) On the response prediction of horizontally loaded fixed-head pile groups in sands. Computers and Geotechnics. J., 37: 930–941.

[19] Poulos, H. G. (1968) Analysis of the Settlement of Pile Groups. Géotechnique, 18: 449–471.

[20] Randolph, M. F., Wroth, C. P. (1979) An analysis of the vertical deformation of pile groups. Géotechnique. J., 29: 423–439.

[21] Randolph, M. F., Wroth, C. P. (1978) Analysis of deformation of vertically loaded piles. Journal of the Geotechnical Engineering Division, 104: 1465–1488.

[22] Salgado, R., Tehrani, F. S., Prezzi, M. (2014) Analysis of laterally loaded pile groups in multilayered elastic soil. Computers and Geotechnics. J., 62: 136–153.

[23] Guoliang, D., Qiyi, Y., Weiming, G. (2012) Study of effective pile length based on Winkler models. Rock and Soil Mechanics. J., in Chinese. 33: 162–166.

[24] Jianqing, Q., Guanbao, Y., Hanchang, F. (2000) Application of the Midlin solver in deformation of soil-cement pile composite foundation. Geotechnical Engineering Technique. J., in Chinese. 1: 17–20.

[25] Linna, S. (2006) Study on settlement and optimum design according to settlement of compsite
foundation. Zhejiang University Publishing, China.