Behavior of Micropiles under vertical tension and compression loads

Comportement des micropieux sous tension et la compression verticale des charges

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ABSTRACT

The use of micropiles has gained widespread attention in many studies and construction works all over the world. Micropiles are small diameter, drilled, cast-in-place grouted piles. They can be used for underpinning works and also in the construction of many newly constructed civil works. The main goal of this paper is to study the axial capacity of micropiles penetrated in granular materials. The methods used to estimate the capacity of micropiles are reviewed. Previous attempts to simulate micropiles in granular material are discussed. In this study, the micropiles and the penetrated soil are modeled using the finite element numerical program PLAXIS. Results of micropiles loading tests carried out in Cairo are utilized to verify and calibrate the finite element model. A parametric analysis was then performed to study the performance of micropiles. The studied parameters include the load-displacement behavior, the soil properties needed in modeling micropiles and the diameter of micropiles under the effect of vertical tension and compression loads.

RÉSUMÉ

L'utilisation de micropieux a gagné l'attention générale dans de nombreuses études et travaux de construction dans le monde entier. Micropieux sont de petit diamètre, percé, exprimés en place jointoyé piles. Ils peuvent être utilisés pour les travaux sous-tendent, ainsi que dans la construction de nombreux travaux de génie civil nouvellement construit. Le principal objectif de ce papier est d'étudier la capacité des micropieux axial pénétré dans des matériaux granulaires. Les méthodes utilisées pour estimer la capacité des micropieux sont passés en revue. Les tentatives précédentes pour simuler micropieux en matériaux granulaires sont discutées. Dans cette étude, les micropieux et le sol a pénétré sont modélisés en utilisant la méthode des éléments finis et le programme de PLAXIS numérique. Résultats des essais de chargement micropieux réalisés au Caire, sont utilisés pour vérifier et calibrer le modèle d'éléments finis. Une analyse paramétrique a ensuite été effectuée pour étudier la performance des micropieux. Les paramètres étudiés comprennent la charge de déplacement de comportement, les propriétés du sol nécessaires à la modélisation micropieux et le diamètre de micropieux sous l'effet de la tension et la compression verticale des charges.

Keywords : Micropiles, Axial capacity, Finite element, Modeling, Coefficient of lateral earth pressure, PLAXIS.

1 INTRODUCTION

Micropiles, root-piles, Mini-piles, Pin-piles and needle-piles are different terminologies for the same concept. A micropile is a small-diameter, drilled and grouted replacement pile that is typically reinforced [FHWA, 2000]. Most micropiles are 100-250 mm in diameter, up to 30 m long and 300 to 1000 kN in compressive or tensile service load [Bruce, 1995]. Structurally, micropiles derive a large portion of their stiffness and strength from high-capacity steel reinforcement elements, which may occupy as much as 50% of the bore volume and hence are used as the main load bearing element. The surrounding grout is used only to transfer the applied load from the steel to the soil by friction. End bearing is not relied on. Hence, the load carrying mechanisms and construction methodology are other characteristics that distinguish micropiles from other cast-in-place pile foundations.

The early use of micro piles was mainly offered in Europe in the 1950's as an ideal safe solution for underpinning foundations of historic buildings being inadequate mainly due to ignorance of the foundation soil properties when these buildings were constructed. Since the needed equipment can operate in locations with low headroom and severely restricted access, micropiles are also used for strengthening foundations of buildings needed to accommodate loads higher than that originally being designed for, which can result in foundations overloading. In addition, micropiles are applied for many other applications. They have been used in the stabilization of embankments, slopes and landslides, increasing stability of structures by reducing settlement and seismic retrofitting. They can also be used in networks for ground improvement and in this case, both vertical and inclined micropiles are utilized to create a geo-composite material with high stiffness and resistance.

The use of micropiles has grown significantly since their conceptions in the 1950's and in particular since the mid-1980s [FHWA, 2000]. In Egypt, the use of micropiles began in the 1990's. An earlier usage of micropiles in Egypt was carried out in 1989 [Hamza Associates, 1989] where micropiles were used as bearing structures of a dormitory building being newly constructed in Cairo. Micropiles of 15 cm diameter and 13-14 m length, reinforced by high tensile steel bars were recommended as bearing structures for part of the project, that have more pronounced effect on neighboring structure, in order to avoid any possible loss of ground and to restore any stress relief in the foundation soil that may result from the pile boring technique. Loading tests on these micropiles proved that they had an ultimate capacity of 100 ton. Micropiles of 15 cm diameter, 12-15 m depth, reinforced by high tensile tube were used also for underpinning the masonry foundations of Al-Azhar mosque, which is one of the oldest big mosques in Cairo [Yousef, 1998] and [Lutfy 1998]. On the other hand, numerical and practical study for underpinning a raft foundation using micropiles in Egypt was discussed by [El-Kadi and Abdel-Fattah, 1998] by

simulating the micropiles as springs with stiffness deducted from a micropile load test. More recently, the soil-micropile interaction was studied by Misra et al., 2004, who proposed analytical solution for micropile design under tension and compression. Also, [Shu, 2005], utilized the finite difference geotechnical software FLAC3D to analyze the performance of micropile in Fontainbleau sand.

To achieve the main goal of this study, the well known finite element program PLAXIS was utilized to simulate the micropiles and the penetrated soil. A 2-D Axisymmetric analysis is carried out for this sake. Since micropiles sustain external loads mainly by skin friction, it was important to determine an optimum value for the coefficient of lateral pressure, K_o, that can be used in PLAXIS to simulate the behavior of micropiles. Then, Load-displacement relationships extracted from the finite element analysis are verified and calibrated using the results of micropiles loading tests carried out in Cairo. The following sections describe the studied case of micropiles and the penetrated soil. The finite element modeling is also discussed. Finally the findings extracted after comparing the finite element results with the field load-settlement results are introduced.

2 MICROPILES TESTS AND SOIL DESCRIPTION

This section is devoted to describe the main specifications of the case study analyzed in this paper. The soil investigations at the site of the analyzed micropiles revealed that the soil consists of a top layer of clayey silt or silty clay of thickness ranging between 0.9 m to 2.2 m. This layer is followed by a sand layer extending to a depth of at least 30 m. The static ground water level is about 3.0m below the surface. Foundation soil varies with depth between medium to very dense state (SPT values in the range of 10 to 70). Based on the SPT test records, the variation with depth of the angle of shearing resistance of the sand is given in Fig, (1).
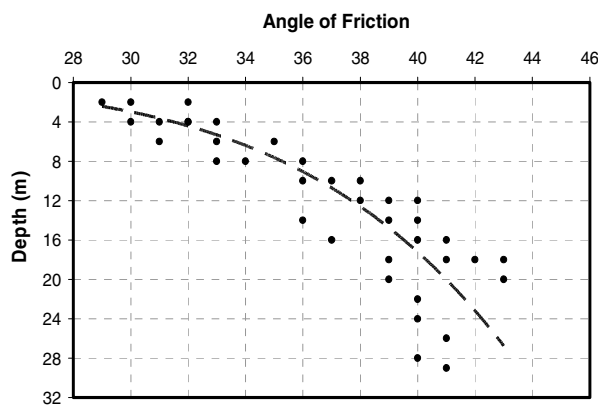

Fig. 1. Variation of angle of shearing resistance with depth.

A micropile of 15 cm diameter and reinforced by 3 high tensile steel bars of 32 mm in diameter was chosen. According to a single micropile design, the chosen micropile allowable capacity is 45.0 ton.

A hole of 150 mm was drilled by rotary percussion to a depth of 13.8 m below the proposed pile cap bottom level. The micropile was constructed using the post-grouting technique. The injection was conducted in intervals, each of 1.0 m, using a packer inside a perforated tube. The size of the project and the well-known dependence of the behavior of micropiles on technological details suggested that some preliminary load tests on piles should be undertaken. Accordingly, the design load has been confirmed by means of two micropile loading tests. The first test was performed on a non-working micropile with a grouted length of 13.80 m. The second test was performed on a

working micropile with a grouted length of 13.0 m. The tests measurements showed that a factor of safety ranging from 2.2 to 2.6 was available against micropiles failure. Finally, it was concluded that the micropiles can safely carry the design load of 45 ton. Results of both tests are illustrated in Fig. (2).
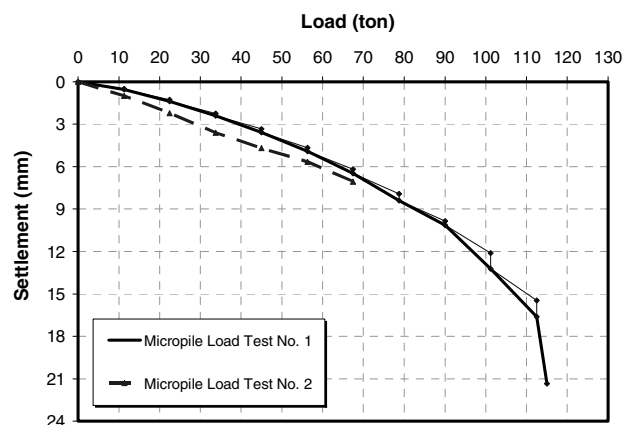

Fig. 2. Load-Displacement curves for micropile loading tests.

3 FINITE ELEMENT MODELING

This section focuses on the finite element modeling of single micropile under axial loading. Detailed finite element analysis has been conducted using PLAXIS to examine the aforementioned case study. The program PLAXIS employs the finite element method and has several different models of soils and rocks. Based on the materials and for mainly sand soil, it is preferable to use the Mohr-Coulomb model for relatively quick and simple and first analysis of any problem considered [Noh et. Al, 2008]. Accordingly, the drained Mohr-Coulomb model (elastic perfectly-plastic behavior) was chosen for modeling sand. This model is determined by five parameters: E –Young's modulus (E), Poisson's ratio (ν), friction angle (φ), cohesion (c) and dilatancy angle (ψ). The micropile was modeled using the Linear Elastic model which can be determined by two parameters: E –Young's modulus (E) and Poisson's ratio (ν). The micropile/soil interface was modeled with frictional interface elements. Summary of the soil properties used in the numerical analysis are illustrated in Table 1

Table 1: Material properties for modeled soil layers.

	Clay	Sand	Penetrated Sand	Sand
Thickness (m)	2.20	1.80	14.0	12.0
Unit weight, γ (kN/m^3)	17.0	10.0	10.0	10.0
Saturated unit weight, γ_{sat} (kN/m^3)	19.0	18.0	19.0	20.0
Cohesion, (kPa)	100	1.0	1.0	1.0
Friction angle, φ	1.0	32.0	37.0	40.0
Dilatancy angle, ψ	0	0	7.0	10.0
Young's modulus, E (MN/m^2)	5	60	120	150
Poisson's ratio, ν	0.30	0.30	0.3	0.2

The term penetrated sand in the table denotes the sand layer where the total length of the micropile is embedded inside in the model. For the micropile, Unit weight, γ, is taken 24 kN/m^3. the micropile is treated as a nonporous material. In addition, the young's modulus of the micropile is calculated as an average weighted young's modulus. This was adopted using the following equation.

$$E_{micropile} = (A_{grout} \times E_{grout} + A_{steel} \times E_{steel})/A_{micropile}$$

According to the [FHWA, 2000], E_{grout} value of 23000 MPa can provide reasonable results for micropiles. Hence, the aforementioned equation results in a micropile modulus of elasticity, $E_{micropile}$, equals 4.8E07 kPa. The poisson's ratio, v, is taken 0.15 for the micropile material.

The geometry Model of micropile in the current study is axisymmetric and the boundary conditions are the standard fixities (vertical geometry lines obtain a horizontal fixity and horizontal lines obtain a full fixity) as shown in Fig. (3). PLAXIS generates automatically a mesh of 15-node triangular elements. On the beginning, the results obtained from micropile loading tests are utilized to verify and calibrate a finite element model. The soil properties needed in modeling micropiles are investigated. Then, a parametric analysis is performed to study the performance of the simulated micropiles. The studied parameters are the load-displacement behavior and the diameter of micropiles under the effect of both vertical tension and vertical compression loads.
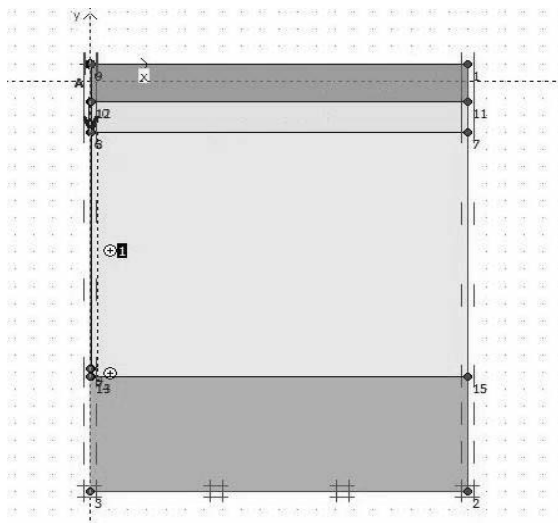

Fig. 3. Axisymmetric modeling and boundary conditions.

4 RESULTS AND DISCUSSION

Speaking about ordinary piles, The Egyptian Code of Practice recommended for driven piles that the coefficient K that relates the vertical overburden stress with the accompanied lateral stress can be taken equals 2.0 when calculating the side friction capacity of the pile. This relatively high value is due to the densification of soil gained during driving the pile inside the soil. On the same way, due to the high pressure grouting used in constructing micropiles, it is expected that the resulting pre-shearing of the soil shall result in turn in increasing the coefficient K.

Based on the above discussion, it was important on the beginning to assign a K value to ensure that the used model can simulate the micropile performance in an accepted manner. The program PLAXIS has the facility of entering values for the coefficient of lateral earth pressure, K_o, for each soil cluster using the known formula $K_o = (1-\sin\varphi)$. For cohesionless material, such as sand, the value of K_o is bounded by the coefficient of passive earth pressure and the coefficient of active earth pressure [PLAXIS, 2002]. According to Table 1, the active and passive pressure coefficients for the sand layer penetrated by the simulated micropile are 0.24 and 4.02 respectively. By default, the program automatically considers that the coefficient K_o for this layer equals nearly 0.40. Hence, a primary run of the PLAXIS program was carried out to investigate the optimum value of K_o that can be adopted in the analysis.

Fig. (4) shows the variation of the load-Displacement behavior of a single micropile using different values of K_o. The studied values begin from a value of 0.50, which is very close to the value automatically calculated by the program. Then, the K_o value was increased in successive runs till reaching a value at which there is a good matching between the load-displacement curves extracted from the software results and the curves representing the field test results. At a K_o value of 2.75 it was found that the ultimate micropile capacity extracted from the numerical analysis is very close to the field test results ($P_{ult}/P_{ult\ test} \approx 92\%$) as shown in Fig. (5).
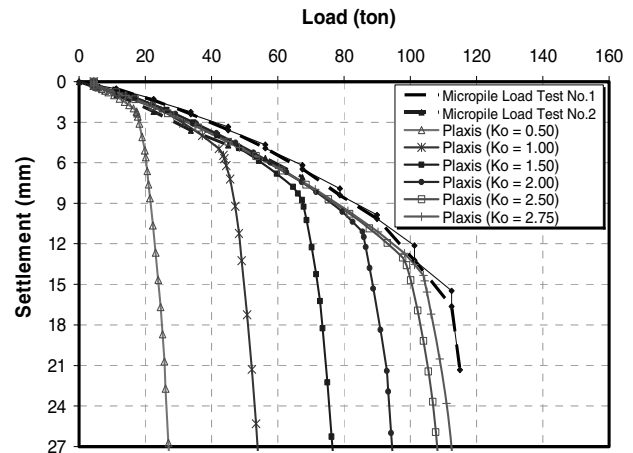

Fig. 4. Load-displacement curves for finite element analysis using different values of Ko compared to experimental field test results.
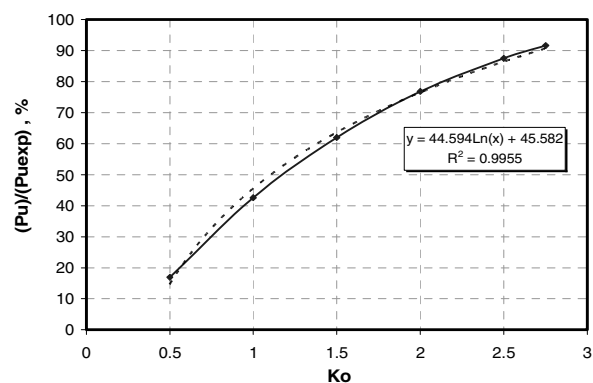

Fig. 5. Effect of Ko on the ratio between numerical and experimental field test results.

The explanation of this relatively high value of K_o that it can be not only due to the pre-shearing of the soil during the grouting process, but also due to the interaction between the soil and the micropiles. This is because the spacing between micropiles in the compared case study was in the range of 0.60 to 1.0 m. In addition, it is worth noting that after performing pulling tests on piles in sand, Ireland [1957] reported that the coefficient K can vary from a value of 1.75 to 3.0 for piles embedded in sand. However, accurate values of the coefficient K for soil penetrated by micropiles need further investigations by cavity expansion tests, which is out of scope of this research.

The effect of micropile diameter on the load-displacement behavior is numerically investigated in both compressive and tensile loading. A constant value of $K_o = 2.75$ is choosen to be used. The micropile diameter ranges from 0.10 to 0.27 m. Figs. (6)-a and (6)-b show the load-displacement curves for different micropile diameters subjected to compression and the tension loads respectively. When comparing the values at the apex of these curves, it can be seen that at relatively low diameters as the diameter increases the contribution of decreasing settlement

or pullout increases rapidly, while for relatively bigger diameters this contribution increases slowly.
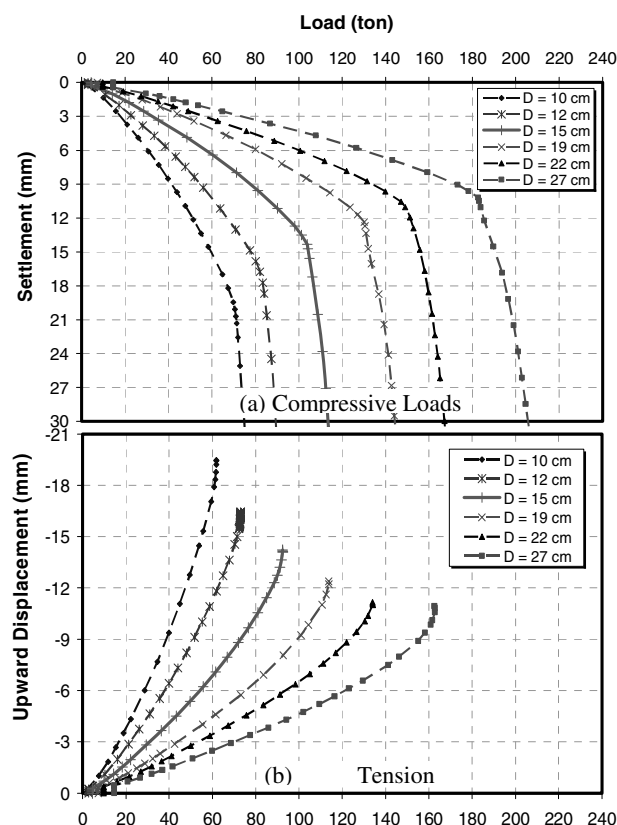

Fig. 6. Load-Displacement curves of different micropile diameters.

The ultimate load versus micropiles diameters are graphed in Fig. (7) for both tension (pullout) and compression loadings. It can be seen that the load direction has a small effect on the ultimate capacity. This is due to the fact that micropile carries the tension or the compression loads by skin friction only. The capacity in tension loading is lower than in compressive loading by about 7 to 12.5 %. However, this small variation can be due to the difference in principal stress direction of both cases.
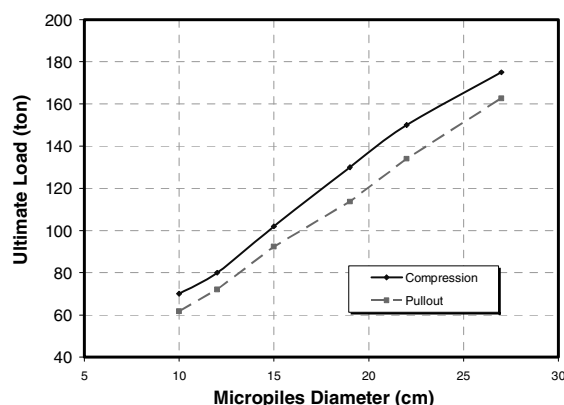

Fig. 7. Comparison between tension and compression behavior of micropiles for different diameters.

5 SUMMARY AND CONCLUSIONS

Results of micropiles field loading tests were utilized to calibrate the analysis of micropiles using the finite element modeling. The PLAXIS 2D program was adopted for this

purpose. For the studied cases, a primary investigation was adopted to find out the optimum value of coefficient of earth pressure, Ko, needed for the numerical simulation. Accepted matching between the field tests results and the numerical results was achieved at a value of $K_o = 2.75$ for the studied case. Then, a parametric study was carried out to investigate the effect of micropile diameter on the loading capacity and displacement of micropile. It was found that for relatively low diameters as the diameter increases the contribution of decreasing settlement or pullout increases rapidly. When investigating the effect of vertical load direction (i.e., compression or tension), it could be seen that the load direction has a small effect on the micropile ultimate capacity. The capacity in tension loading was found lower than in compressive loading by about 7 to 12.5 %. It can be concluded that the adopted simulation of micropiles using the PLAXIS program gives satisfactory results.

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