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Analysis of Micropile Constructed in Sandy Soil of Ismailia Area

K. Hafez[1], A.Moubarak[2], A. Hamad[3]

[1] Professor, Faculty of Engineering, Suez Canal University, Egypt.
[2]Assistant professor, Faculty of Engineering, Suez Canal University, Egypt.
[3]Assistant Lecturer, wassit University, Iraq.

ABSTRACT

The main object of the paper is to study the behavior of Micropile in sandy soil of Ismailia. A full scale field test result on Micropiles in USA for rocky soil are numerically verified using the finite element analysis software ABAQUS. Then, the verified numerical model of the software ABAQUS is used to curry out the analysis of Micropiles constructed in sandy soil of Ismailia area. Numerical results obtained are very close to the field results. The chosen model is suitable for initial prediction of the behavior of micropile instead of field tests which take more time and cost. Results indicated that, application of the combined load on the micropile causes a decrease in the lateral displacement and bending moments compared with application of the lateral load at Ismailia site (sandy soil). The effect increasing the diameter by 50[%] on the behavior of the micropile is reducing the axial displacement by 22[%] and increasing the axial ultimate load by 30[%]. The lateral loading results indicate that the lateral displacement is reduced by 43.5[%] and the lateral ultimate load increases by 35.1[%], whereas the maximum bending moment increases by 192.4[%]. The combined loading results show that the lateral displacement is reduced by 40.4 [%] and the lateral ultimate load increases by 41[%], but there is more change in the maximum bending moment which increases by 292[%]. The study also presents guidelines and diagrams for the similar sites for different types of load.

KEYWORDS: Micropile; 3D finite element analysis; Soil–Micropile interaction; Combined loads; Rocky soil; Sandy soil.

ملخص

الهدف الرئيسي من هذه الورقة هو دراسة سلوك الخازوق الابري المنفذ في التربة الرملية في الإسماعيلية. تم التحقق من نتائج الاختبارات الحقلية للخوازيق الابرية المنفذة في الولايات المتحدة الأمريكية للتربة الصخرية عدديا باستخدام برنامج التحليل بالعناصر المحددة (ABAQUS). ومن ثم تم استخدام هذا البرنامج لتحليل الخازوق الابري المنفذ في التربة الرملية في منطقة الإسماعيلية. النتائج العددية التي تم الحصول عليها قريبة جدا من النتائج الحقلية. النموذج المختار هو جيد للتنبؤ بسلوك الخوازويق الابرية بدلا من الاختبارات الحقلية التي تأخذ المزيد من الوقت والتكلفة. وأظهرت النتائج أن تسليط الحمل المركب على الخازوق الابرية المنفذ في الإسماعيلية (التربة الرملية) يؤدي إلى التقليل في الازاحة الجانبية وعزم الانحناء مقارنة مع تسليط الحمل الجانبي فقط. تأثير زيادة القطر للخازوق الابري بنسبة 50[٪] يؤثر على سلوك ميكروبيل في التحميل المحوري يقلل الازاحة المحورية بمقدار [٪] 22 وزيادة الحمل التصميمي المحوري بنسبة [٪] 30. وتظهر النتائج في التحميل الجانبي إلى أن الازاحة الجانبية تقل بنسبة 43.5[٪] ويزيد الحمل التصميمي الجانبي بنسبة [٪] 35.1 ، في حين أن عزم الانحناء يزيد بمقدار [٪] 192.4. وتظهر نتائج التحميل المركب أن الازاحة الجانبية تقل بنسبة [٪] 40.4 ويزيد الحمل التصميمي الجانبي بنسبة 41 [٪]،في حين أن عزم الانحناء يزيد بمقدار [٪] 292. كما تقدم الدراسة مبادئ توجيهية ومخططات لمواقع مماثلة لأنواع مختلفة من الحمل.

1. INTRODUCTION

Micropiles are defined in geotechnical engineering as a small-diameter pile, grouted after drilling the pile, the commonly used diameter of micropile range between 100 to 300 [mm], and the length of micropiles range between 5 to 30 m. It is slender in nature, having a small diameter to length ratio, finishing in a majority of load transfer to the soil depending on friction along the surface of the pile for capacity, resulting in design as a friction pile, the micropiles can withstand axial and lateral loads.

(FHWA [1]). Micropiles used their debut as a lower cost suitable way to retrofit existing old historical buildings. In the middle of the last century, the use of micropiles has increased in most parts of the world. It can be used in new innovative ways in the last 20 to 25 years for small bridges, buildings in congested areas, slope stability, seismic remediation, electrical towers, residential construction. It can support both axial and lateral loads (combined loading) beneath structures. The use of micropiles in more of these situations is relatively new. Micropiles alluring in hard boring zone and comprise of any blend of grout, rebar, empty bar, steel stick, and steel packaging. The grout is either placed or infused under weight around 0.8 to 1 [MPa]. Micropile has many names such as stick heaps, minipiles, needle heaps, root heaps, and grating (FHWA [1]).

2. MODELING OF MATERIAL

The numerical study of this research has been carried out by the program ABAQUS, which can analyze micropiles and different types of soil using different subsoil models. In the analysis, 3-D finite element model for the micropiles and soil are used. The model cannot be simulated as two-dimensional as long as there is a lateral load and the model must be treated using a three-dimensional analysis (Helwany [2]). The micropile model consists of two basic materials (steel and grout). The steel casing is modeled as linear elastic behavior described by the Poison's ratio of 0.25 and Young's modulus of 2000000[MPa].The soil is modeled as elasto-plastic model. The Mohr-Coulomb is a part of the constitutive soil model. Two types of soils are studied, the first site is the state of Missouri in the United States of America constructed in rocky soil that consists of two layers: the first layer is stiff to hard clay and the second layer is shale rocky soil, as shown in Figure 1. The second site in Egypt at Ismailia which contains sandy soil, consists of four layers: the first and the second layers are medium dense sand, the third layer is medium to fine loose sand and the forth layer is medium dense sand as shown in Figure 2. The interaction between the outer side of the micropile (casing and bond) is designed on friction values is simulated using penalty-type interface between the casing and the soil on the one hand and between bond and soil on the other hand. Different friction coefficients are used in micropile ranging from (0.47 to 0.6). The interaction between the outer side of the micropile (casing and bond) is designed on friction values is simulated using penalty-type interface between the casing and the soil on the one hand and between bond and soil on the other hand. Different friction coefficients are used in this case ranging between (0.23 to 0.45). The grouted material is modeled as linear elastic behavior described by the Poison's ratio of 0.25 and Young's modulus of 25[MPa].

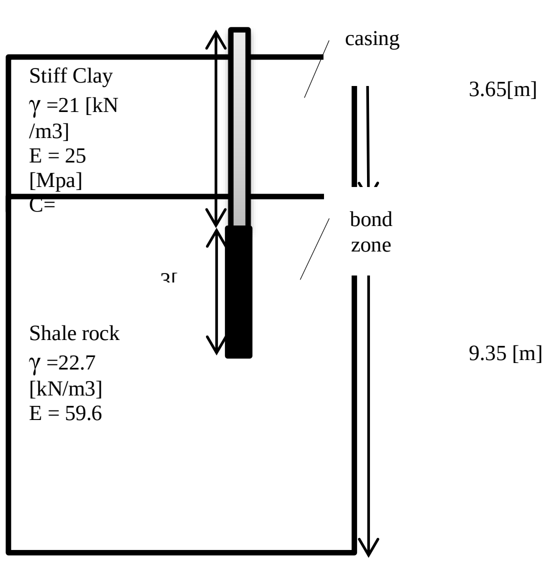

Figure 1 Site 1 USA (Rocky soil)

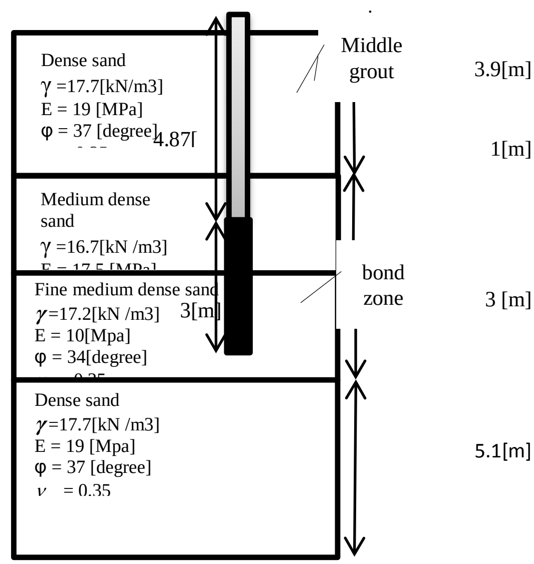

Figure 2 Site 2 Ismailia, Eygpt (Sandy soil)

Notes: γ= unit weight; E= Elastic Modulus; φ = Friction Angle; ν = Passion's Ratio

The properties of the Micropile are shown in Table 1.

Table 1 Micropile Properties.

Element	*L [m]*	*OD [cm]*	*E [MPa]*	*ν*	*γ [kN/m3]*
Cased Zone (Steel)	**4.87**	**17.8**	**200000**	**0.2**	**75.5**
Middle grout (concrete)	**4.87**	**15.6**	**20000**	**0.25**	**23.5**
Bond Zone (concrete)	**3**	**20**	**20000**	**0.25**	**23.5**

Notes: L= length of element; OD= Outer Diameter E= Elastic Modulus; ν = Passion's Ratio; γ= unit weight

The ABAQUS symmetry feature is used to reduce the number of degrees of freedom (DOF) and consequently the number of elements and the overall mesh size. Then, The analysis can be performed on half of the soil and micropile to reduce the computational time. In this model, the symmetry is used on the axis which contains the pile and the line of action of the combined load as shown in Figure 3. The side distance of the model should not be less than 50 times the pile diameters as measured from the center of the pile (Randolph and Wroth [3]). Helwany made the axisymmetric model in the ABAQUS program to simulate the behavior of piles. Vertical distance under micropile in soil should be greater than 70[%] of the pile length (Helwany [2]). The model consists of two parts: the first one is the micropile, while the second is the soil. The micropile with diameter 0.178[m] and length 7.87 [m]and the soil is 20 [m] width (in the x-direction), 10 [m] wide (in the y-direction), and 13 [m] depth (in the z-direction) as shown in Figure 4.

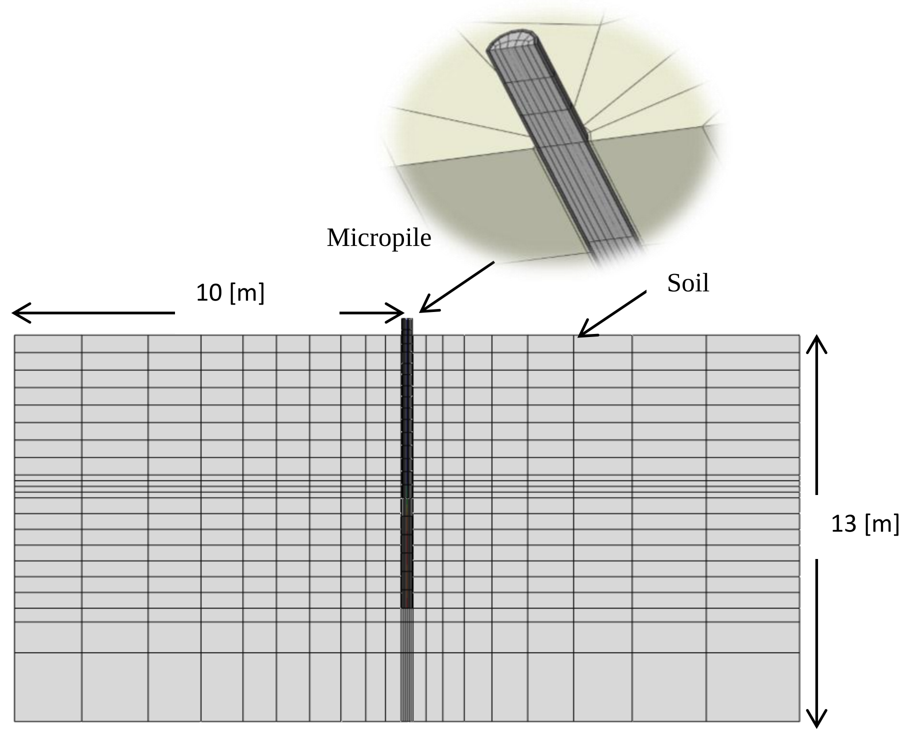

Figure 3 Finite element discretization (Elevation)

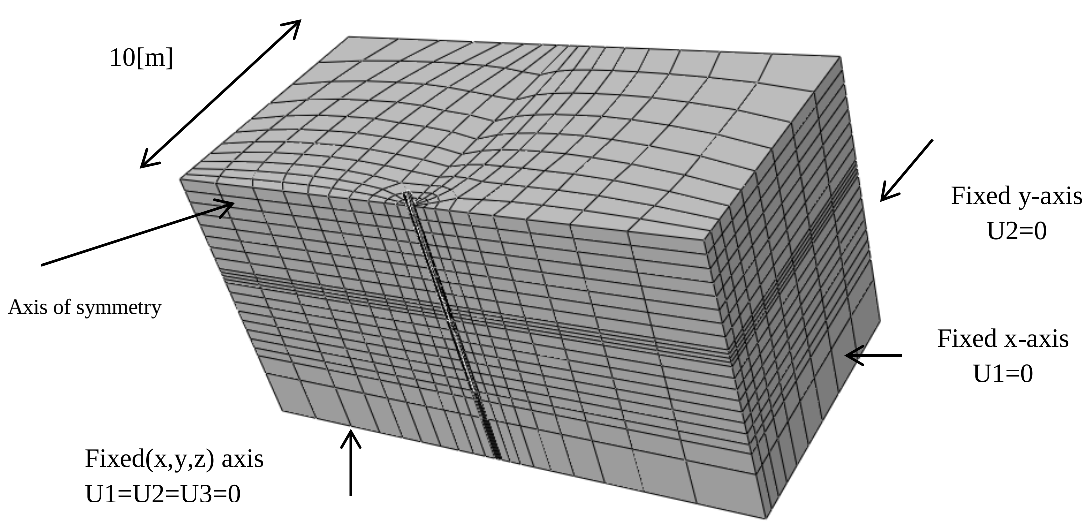

Figure 4 Finite element discretization (Boundary conditions).

After the geometry model is complete, the mesh is working through this step. The model consists of two main parts of the micropile and soil. The micropile consists of the casing inside concrete and bar reinforcement, and bond zone having an 8-node linear brick element. The number of elements of casing, bond zone, grout and soil are (128,228,352 and 352) respectively, as shown in Figure 3 and Figure 5

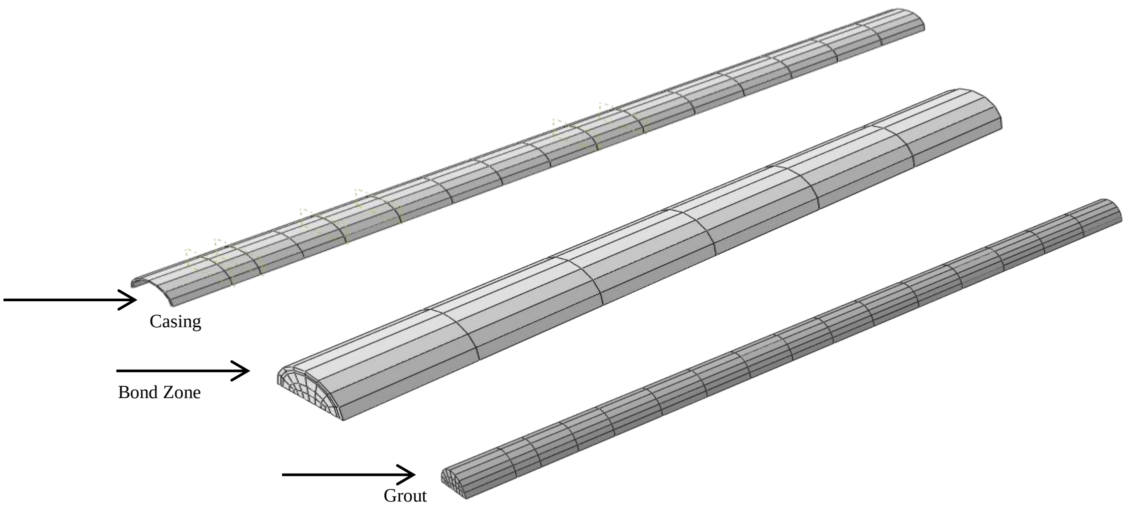

Figure 5 Mesh of (casing, bond zone and grout inside steel pipe).

3. MODEL VERIFICATION

The numerical model is first verified using the same micropile model and the same loads the site in the state of Missouri at United States of America according to (Kershaw [4]) as shown in Figure 1. The test results of this research are modeled by using ABAQUS program are compared with field results of the (Kershaw [4]). A numerical model was created to simulate the micropile-loading test (axial, lateral and combined) in the field test as shown in Figure 4. The model is symmetric, and thus half of the model is used in the analysis.

3.1. Axial load results

A load cycle sequence which used in the analysis is presented in Table 2. The results are shown in Figure 6 to investigate the behavior of the micropile. The numerical (dotted) results are compared with field values (full line).

Table 2 Axial loads sequence FHWA [1]

	Axial loads	**Time [min]**
Alignment loads	**AL**	**2.5**
Cycle 1	**0.15 D.L**	**2.5**
	0.3 D.L	**2.5**
	0.4 5D.L	**2.5**
	0	**1**
Cycle 2	**0.15 D.L**	**1**
	0.4 5D.L	**1**
	0.6 D.L	**2.5**
	0.75 D.L	**2.5**
	0.9 D.L	**2.5**
	1 D.L	**2.5**
	0	**1**
Cycle 3	**0.15 D.L**	**1**
	1 D.L	**1**
	1.15 D.L	**2.5**
	1.3 D.L	**10**

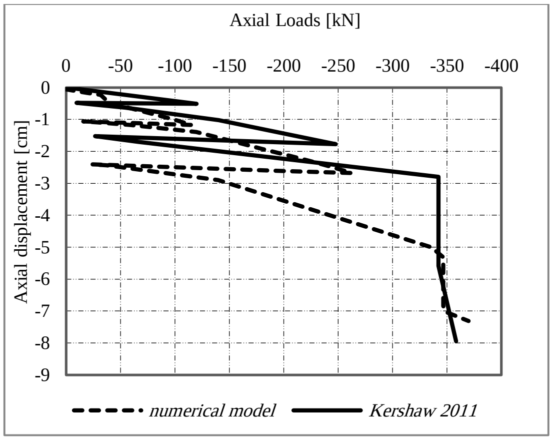

Figure 6 (Axial loads vs. Axial displacement)

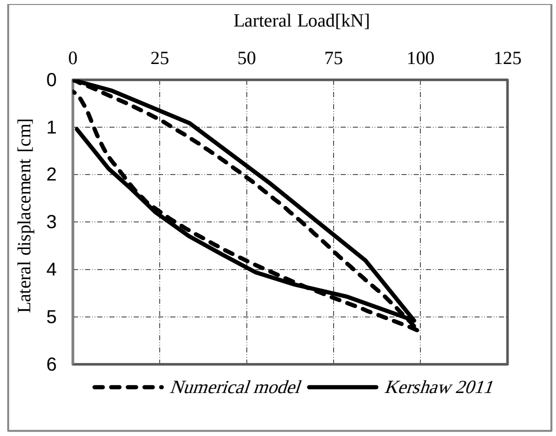

Figure 7 (Lateral load vs. Lateral displacement)

3.2. Lateral load results

A load cycle sequence is used in the analysis as shown in Table 2. Figures 7 and 8 show that the numerical results are approximately coincide with Kershaw results for the lateral loads.

Table 3 lateral loads sequence

Lateral Loads		Hold
[kips]	**[kN]**	**[min]**
Alignment Loads		**2.5**
0.5	**2.2**	**2.5**
1	**4.4**	**2.5**
2.5	**11.1**	**2.5**
5	**22.2**	**2.5**
7.5	**33.3**	**5**
10	**44.4**	**5**
12.5	**55.5**	**5**
15	**66.6**	**5**
17	**75.5**	**5**
18	**80**	**5**
19	**84.4**	**5**
20	**88.8**	**5**
22.5	**100**	**5**
15	**66.6**	**2.5**
10	**44.4**	**2.5**
5	**22.2**	**2.5**
Alignment Loads		**2.5**

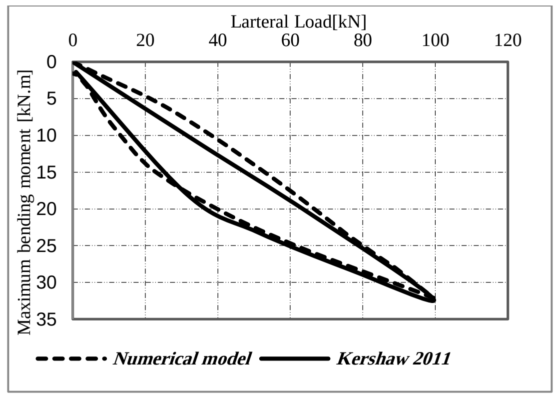

Figure 8 (Lateral load vs. Maximum bending moment)

3.3. Combined load results

In Kershaw 2011 a constant axial load equals to one-half of the ultimate axial capacity 177.7 [kN] was placed on the micropile. Then, the lateral loads are incrementally applied near the top of the micropile at approximately 0.3 [m] below the pile head (top), as shown in Table 2. Figures 9 and 10 illustrate also that the combined load results of the present study are similar to Kershaw 2011 results.

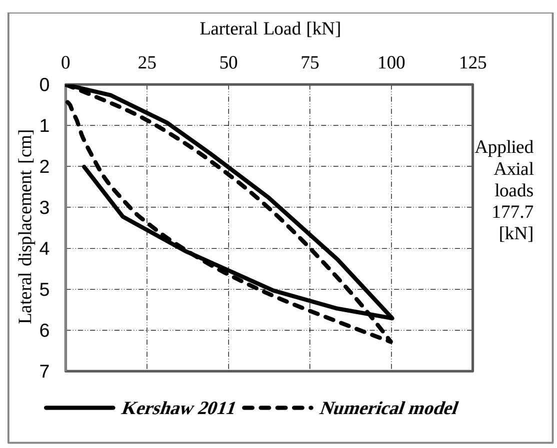

Figure 9 (Combined load vs. Lateral displacement)

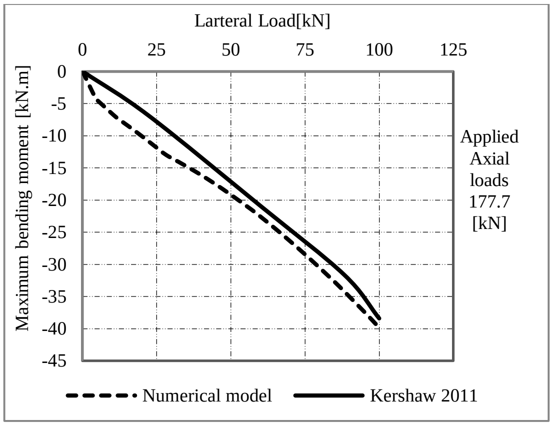

Figure 10 (Lateral load vs. Maximum bending moment)

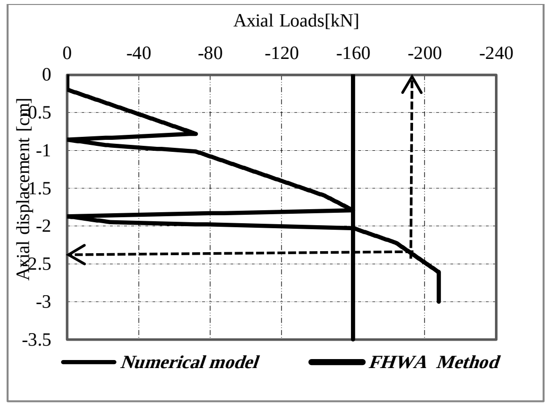

Figure 11 Relation between axial loads and axial displacement of Micropile in Ismailia site

4. Numerical Results and Discussion

4.1. Behaviour of the micropile in Ismailia site (sandy soil)

Figure 2 and Table 1 show the plan view and materials properties of sandy soil and cross section of Micropile tested in the field (Kershaw [4]). The numerical model which shown in Figures 3 and 4 is used in the three dimensional analysis in ABAQUS program. The load is applied in three conditions, vertical, lateral and combined loads.

4.1.1. Axial load results

Axial load is applied according to the load sequence shown in Table 2 The allowable geotechnical bond capacity of the micropile for axial load of sandy soil was calculated from equation 1 (FHWA [1]).

$$\mathbf{P}_{\mathbf{G\text{-}allowable}} = \frac{\boldsymbol{\alpha}\ \mathbf{bond}}{\boldsymbol{F.s}} \times \boldsymbol{\pi} \times D_b \times L_b \qquad \ldots\ldots.. \ 1$$

where:

α_{bond} = grout to ground ultimate bond strength

FS = factor of safety applied to the ultimate bond strength; herein, a factor of safety of 2.0

D_b = diameter of the drill hole; and

L_b = bond length

The value of α-bond (Grout-to-Ground Bond) for micropile design for the second and third layer of the medium dense sand and fine dense sand is equal to 248 [kPa] for Ismailia site. (FHWA [1]).

In the previous equation, the allowable load of sandy soil was 160 [kN], then simulated in the ABAQUS program.

Figure 11 shows the value of the maximum axial displacement of the micropile in the site of Ismailia (sandy soil) equals 3.02[cm] when applied the loads are as presented in Table 2. The allowable load took place at a total displacement of 0.15 [mm/kN] (160×0.15) = 2.4 [cm]. The axial allowable load predicted by (FHWA [1]) and the numerical model results are shown in Figure 11 and equal to (160, 185.2)[kN] respectively with an increase of 16[%].

4.1.2. Lateral load results

Lateral load is applied according to the load sequence presented in Table 3.

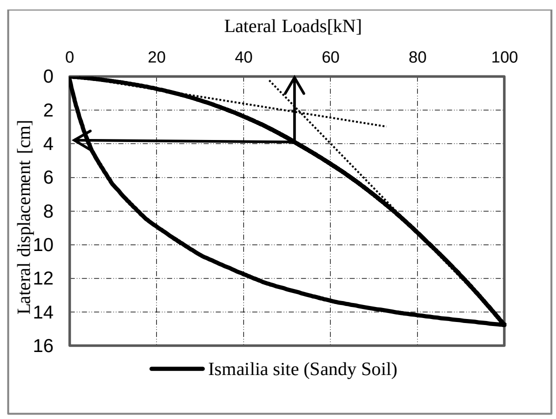

Figure 12 Relation between lateral loads and lateral displacement of Micropile

Figure 12 shows the failure criteria applied to the lateral load-displacement curves for the micropile in Ismailia site. The interpreted failure load of the micropile according to the failure criteria of Butler and Hoy (1977) intersection tangent method. Considering the load at the intersection of tangent sloping and tangent to the initial straight portion of the total settlement curve, the approximate ultimate loads is equal to 52 [kN] and the lateral displacement is equal to 4 [cm].

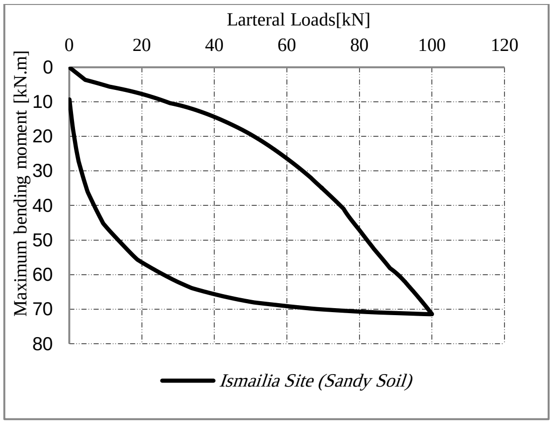

Figure 13 Relation between lateral loads and maximum bending moment of Micropile

Figure 13 shows the relation between the lateral load and the maximum bending moment of the micropile. The values of the maximum bending moment of sandy soil, Ismailia site, is equal to 71.4 [kN.m]. The allowable bending moment of the micropile for the lateral load of sandy soil is calculated from equation 2 (FHWA [1]).

$$M_{allowable} = 0.55Fy * \frac{I}{OD/2} \quad \ldots\ldots 2$$

$M_{allowable}$ = allowable bending moment
I= moment of inertia for casing
OD= Outer Diameter of casing

From the previous equation, the calculated allowable bending moment is equal to 204.5 [kN.m].

$M_{allowable}$ 204.5 $>$ 71.4 ok .

4.1.3.Combined load results

A constant axial load equal to one-half of the ultimate axial capacity 80 [kN] is applied on the micropile. Then, the lateral loads are incrementally applied near the top of the micropile approximately the lateral loads incrementally applied near the top of the micropile at approximately 0.3 [m] below the micropile head, as shown in Table 2.

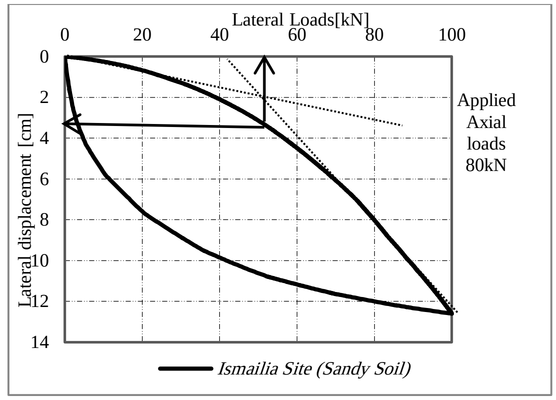

Figure 14 Relation between combined loads and lateral displacement of Micropile

Figure 14 shows the failure criteria applied to the combined load-displacement curves for micropile in Ismailia site. The interpreted failure load of the micropile according to the failure criteria of Butler and Hoy (1977) is the intersection tangent method (NYSDOT [5]). The load at the intersection of tangent sloping and tangent to the initial straight portion of total settlement curve can be approximately equal to the ultimate load of 50.2 [kN], and lateral displacement is equal to 3.2 [cm].

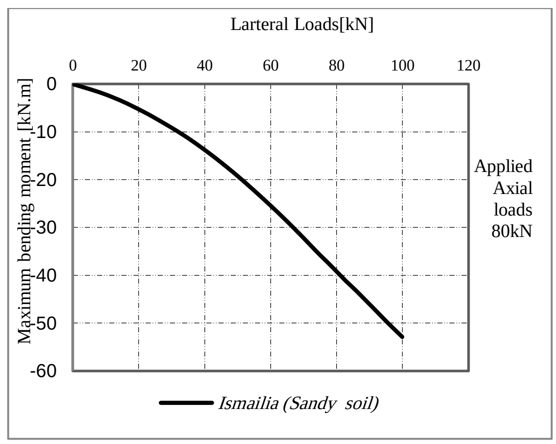

Figure 15 Relation between combined loads and maximum moment of Micropile

Figure 15 shows the relation between the combined loads and the maximum bending moment of the micropile. The values of the maximum moment is 52.9 [kN.m]. From equation 2, the allowable bending moment of 204.5 [kN.m] was calculated.

$M_{allowable}$ 204.5 $>$ 52.9 ok.

4.2. Comparison between results of the lateral and combined loads applied on the micropile

The main objective of this research is to analyze the behavior of micropiles in sandy soil. Comparison between the results is performed to investigate the effect of axial load on the lateral behavior of micropiles under the effect of the combined loads.

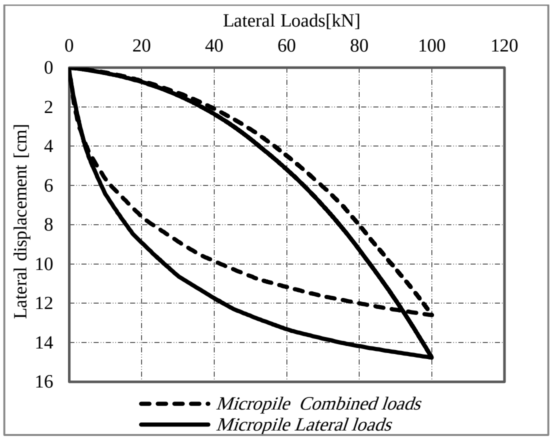

Figure 16 Lateral and Combined vs. lateral displacement in Ismailia site

When comparing the results of the lateral load and combined load versus lateral displacement, the lateral displacement for both cases was the range (0 to 26) [kN]. The difference in the value of the lateral displacement clearly begins when the loads reach 26 [kN]. It's clear that the displacement of the combined loads is smaller than the displacement of lateral loads (13.5, 14.7) [cm] respectively by approximately 8.1[%].

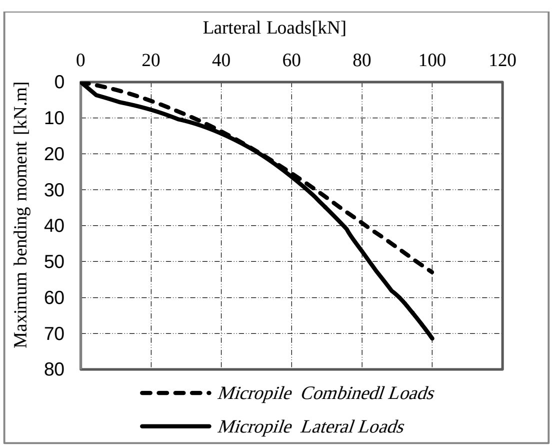

Figure 17 Lateral and Combined Load vs. Maximum Bending Moment in Ismailia site

As illustrated in the Figure 17, the difference between the maximum bending moments in case of the lateral and combined loading is equal to (71.4 and 52.9) [kN.m] respectively. These results were expected because the results of lateral displacement versus combined loads and lateral loads respectively, as shown in Figure 16, was the displacement of combined loads smaller than the displacement of lateral loads because the maximum bending moment is depending on the lateral displacement.

Finally, results in Figure 16 and 17 show that combined loading, causes reduction in lateral displacement and moment compared to the lateral loading.

4.3. Effect of applied lateral and combined loads on moment along micropile depth

For a comprehensive study of the micropile, the percentage of the lateral and combined loads is increased. The maximum bending moments at various depths are calculated to determine the critical depth of the micropile at which the maximum bending moment takes place.

4.3.1. Effect of lateral load value on moment versus depth

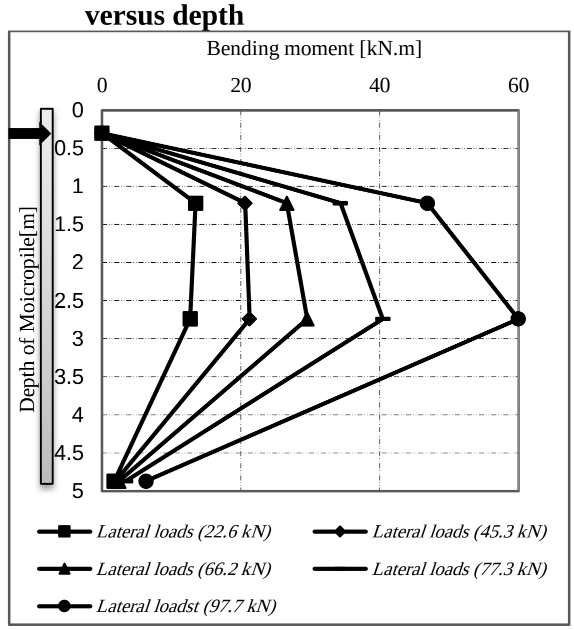

Figure 18 (Moment vs. Depth) due to lateral load

When applying a lateral load of 22.6 [kN], as shown in Figure 18, it is noticed that the magnitude of the bending moment is equal to zero at the depth of 0.3[m]. At a depth of 1.22 [m] the value begins to increase, and at a depth of 2.74[m] till reaching the peak, then decreases. When the load is increased from 22.6 to 97.7 [kN], the maximum bending moment at depth 2.74[m] in the sandy soil of the Ismailia increases to 59.9 [kN.m], as shown in

Figure 18. This increase in the bending moment in the sandy soil of the curved distribution is acceptable because it is less than the allowable bending moment of the micropile section.

$M_{allowable}$ 204.5 > 59.9 ok.

4.3.2.Effect of combined value load on moment versus depth

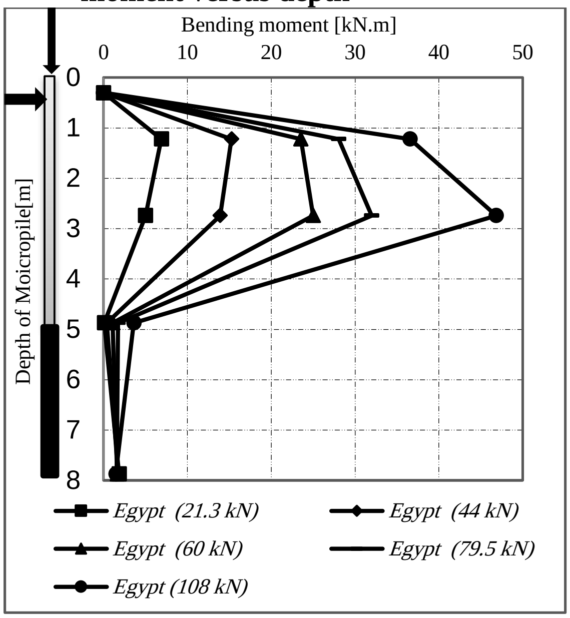

Figure 19 (Moment vs. Depth) due to combined load

When applying a lateral load of 21.3 [kN] as shown in Figure 19, it can observed that the magnitude of the bending moment equals to zero at the depth of 0.3[m], and the value begins to increase from 1.2[m] to 2.74[m] until it reaches the peak and then decrease until it reaches close to zero at 4.87 [m] and 7.87[m] depth.

When the load is increased from 21.3 to 108 [kN], the maximum bending moment at depth 2.74[m] in the sandy soil of the Ismailia increases to 46.8[kN.m], as shown in Figure 17. This increase in the bending moment in the sandy soil of the curved distribution is acceptable because it is less than the allowable bending moment of the micropile structural section.

$M_{allowable}$ 204.5 > 46.8 ok

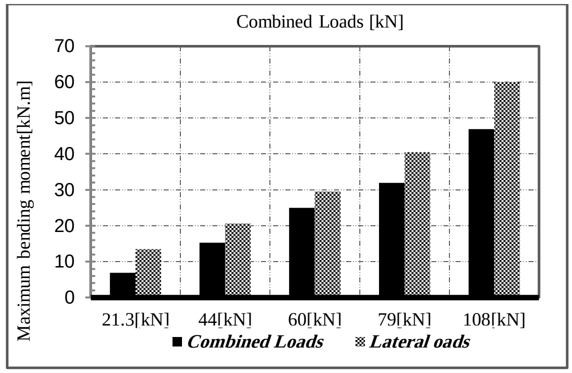

Figure 20 Maximum moment vs. Various combined loads

When comparing the lateral and combined loads versus maximum bending moments, Figure (20) shows that the maximum bending moment that the maximum bending moments for the cases of lateral and combined loading are equal to (59.9 and 46.8)[kN.m] respectively. These results were expected because of the difference between the calculated lateral displacements in both cases, as presented in Figure (16).

4.4. Effect of micropiles diameter

In this section the diameter of the micropile increased from 0.178[m] to 0.27[m] or increased by 50[%] for sandy soils. Then comparison between the results of each case is presented herein below:

4.4.1.Axial load results

The Micropile is simulated by the ABAQUS program under the effect of axial cycle load as in Table 2 in sandy soil for the same specifications as Kershaw 2011 except the diameter are increase by 50[%].

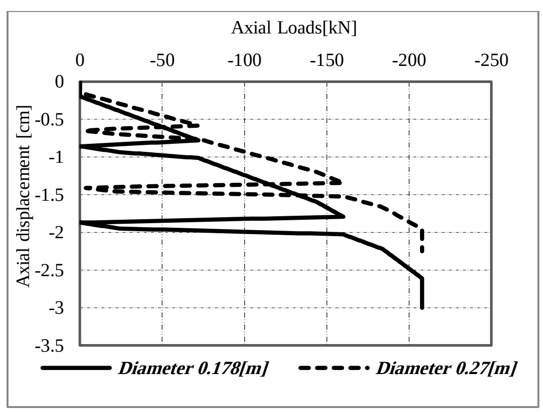

Figure 21 Relation between axial loads and axial displacement of Micropile (Ismailia Site)

Figure 21 illustrates the axial displacement versus axial load at the micropile head after changing the micropile diameter. In Ismailia site at diameter of 0.178[m], [0.27[m] the axial displacements are

equal to 2.57 [cm], 2 [cm] respectively. It can be observed that at an axial of displacement 2.25 [cm] the loads increased from 160[kN] to 208[kN] when increasing the diameter from 0.178[m] to 0.27[m].
These results show that when the micropile diameter is increased by 50[%], the axial displacement decreases by 22[%] and the load increases by 30 [%] at a displacement of 2[cm].

4.4.2.Lateral load results

The micropile is modeled by the ABAQUS program under the effect of lateral cyclic load, as presented in Table 3, for the same micropile configuration used in Kershaw 2011 except for increasing the diameter by 50[%].

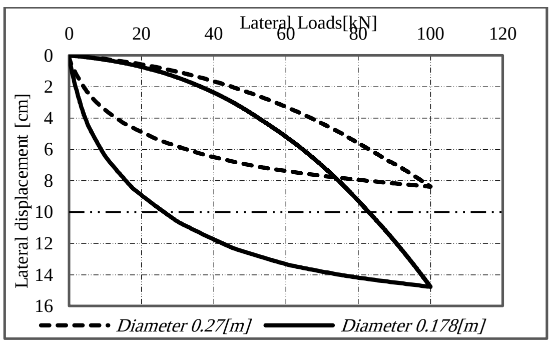

Figure 22 Relation between lateral loads and lateral displacement of Micropile (Ismailia Site)

Figure 22 illustrates that the lateral displacement versus lateral load for the micropile after changing the diameter of the micropile. In Ismailia site at diameter 0.178 [m], and 0.27 [m] the lateral displacements are equal to 14.7 [cm], 8.3 [cm] respectively. It can observed that at a lateral displacement of 8.3 [cm] the loads increased from 73.9 [kN] to 99.9 [kN] when increasing the diameter from 0.178 [m] to 0.27 [m]. In addition, when the diameter is increased by 50[%], the lateral displacement decreases by 43.5[%] and the load increases by 35.1[%] at 8.3 [cm].

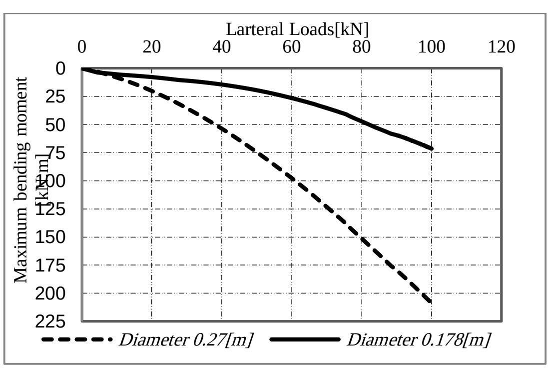

Figure 23 Relation between lateral loads and maximum bending moment of Micropile (Ismailia Site)

Figure 23 shows the relation between the lateral loads and the maximum bending moment at the micropile after changing the diameter of the Micropile. In Ismailia site at diameter 0.178[m], 0.27[m] the maximum bending moments are equal to 71.4 [kN.m], 208.8 [kN.m] respectively. However, when the diameter is increased by 50[%], at load of 100[kN] the maximum bending moment decreases by 192.4[%].

From equation 2, the allowable bending moment is equal to 204.5 [kN.m].
$M_{allowable}$ 204.5 $<$ 208.8 Not ok.
This increase in the bending moment in the sandy soil requires changing the micropile properties to resist the large bending moment. Thus, an increased thickness in addition to steel reinforcement inside the casing is needed to resist the relatively large bending moments resulting from the diameter change.

4.4.3.Combined load results

The micropile was modeled by the ABAQUS program under the effect of axial load of 80[kN] which is held constant and then incrementally applying the lateral loads near the top of the Micropile approximately 0.3[m] below the micropile head, as shown in Table 3 using the same configurations studied in Kershaw 2011, except for increasing the diameter by 50[%].

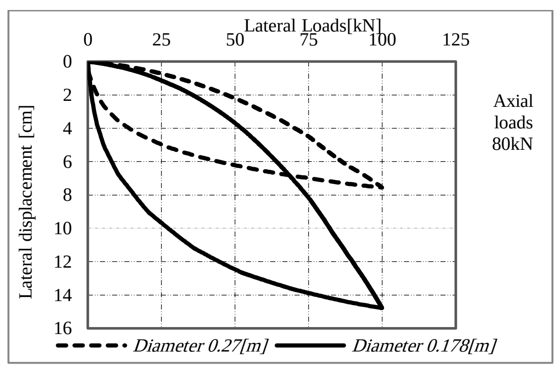

Figure 24 Relation between combined loads and lateral displacement of Micropile (Ismailia Site) .

Figure 24 shows the relation between the lateral displacement and combined load for the micropile after changing its diameter. In Ismailia site changing the diameter from 0.178[m] to 0.27[m] the computed lateral displacements are equal to 12.6 [cm] and 7.5 [cm] respectively. It can observed that at lateral displacement of 7.5 [cm] the loads increased from 70.9 [kN] to 99.9 [kN]and the lateral displacement is reduced by 40.4[%] and the load is increased by 41[%] at lateral displacement of 7.5 [cm].

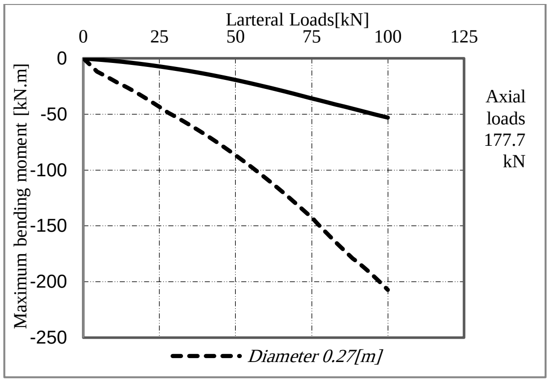

Figure 25 Relation between combined loads and maximum bending moment of Micropile (Ismailia Site).

Figure 25 illustrates the combined loads versus maximum bending moments at the micropile after changing the diameter of the micropile. Increasing the diameter from 0.178[m] to 0.27[m] resulted in increasing the maximum bending moment from 52.9 [kN.m] to 207.4 [kN.m] respectively. In addition, increasing the diameter by 50[%], at loads 100[kN] the maximum bending moment is decreased by 292[%].

$M_{allowable}$ 204.5 < 207.4 Not ok. This increase in the bending moment in the sandy soil requires changing the micropile properties to resist the larger bending moment. In other words, the casing thickness should be increased in addition to adding steel reinforcement inside the casing.

5. Conclusions

1. ABAQUS software was capable of simulating the micropile field tests performed by (FHWA [1]).regarding the axial behavior. In addition the software was capable of accurate simulation of the lateral displacements and bending moments under lateral loads, and of the lateral displacements and bending moments under the combined axial and lateral loads.
2. For micropile in Ismailia site (sandy soil), the applied combined load has noticeable effect on lateral micropile behavior. The observed changes are reductions in the lateral displacement by 14.2[%] and bending moment by 26[%] compared to the lateral load tests as in (Klein and Karavaev [6]), (Karasev, Talanov [7]), (RAMASAMY [8]), (Saxena [9]), and (Jain, Ranjan [10]).
3. Changing the micropile diameter from 0.178[m] to 0.27[m] in the Ismailia site (sandy soil) resulted in reducing the axial displacement by 22 [%] and increasing the axial ultimate load by 30[%] at the least displacement.
4. The lateral loading results indicated that the lateral displacement is reduced by 43.5[%] and the lateral ultimate load is increased by 35.1[%], and the maximum bending moment is increased by 192.4[%].
5. The combined loading results showed that the lateral displacement is reduced by 40.4 [%] and the lateral ultimate load is increased by 41[%], but the change in the maximum bending moment is increased by 292[%].

The increased bending moments along the micropile section may need increasing the steel casing thickness and adding steel reinforcement bars inside the casing.

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