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BEHAVIOR OF PILE GROUPS UNDER LATERAL LOADS IN SAND SOIL CONSIDERING MOHR-COULOMB AND MODIFIED MOHR-COULOMB CRITERIONS: COMPARATIVE ANALYSIS

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ABSTRACT:

The behavior of pile groups under lateral loads depends on the soil-structure interaction which is governed by the soil properties and behavior. In the three-dimensional finite element analysis, the prediction of the realistic soil behavior is a complex step in order to capture the realistic pile-soil interaction. In the analysis programs, the soil behavior can be defined using constitutive models like the Mohr-Coulomb constitutive model which is widely used in representing the soil layers in the analysis, but a new modified constitutive model called the Modified Mohr-Coulomb model also used in the analysis along with other constitutive models. The goal of this research is to compare the two constitutive models' capacity to capture the behavior of a full-scale pile group case study and validate the results to field measurements. A good agreement is found between the measured and the computed behavior of pile groups under lateral loads using the Modified Mohr-Coulomb constitutive model.

KEYWORDS: Constitutive models, **Modified Mohr-Coulomb**, **Mohr-Coulomb**, **Pile Group**, **Lateral Load**

دراسة عددية مقارنة:سلوك مجموعات الخوازيق تحت تأثير الأحمال الجانبية في التربة الرملية

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الملخص:

يعتمد سلوك مجموعات الخوازيق تحت تأثير الأحمال الجانبية على التفاعل بينها وبين التربة والذي تحكمه خصائص التربة وسلوكها. في تحليل العناصر المحدودة ثلاثي الأبعاد ، يُعد التنبؤ بسلوك التربة الواقعي خطوة معقدة لالتقاط تفاعل

واقعي بين التربة و الخوازيق. فعادةً يستخدم نموذج مور- كولومب على نطاق واسع في تمثيل طبقات التربة وسلوكها في التحليل العددي، ولكن يتم أيضاً استخدام نموذج جديد مُعدل يسمى نموذج مور- كولومب المُعدل في التحليل العددي جنبًا إلى جنب مع النماذج الأخرى. الهدف من هذه الدراسة هو مقارنة قدرة النموذجين سالفي الذكر في التقاط سلوك مجموعة الخوازيق تحت تأثير الحمل الجانبي ومقارنة النتائج مع القياسات الميدانية. لوحظ اتفاق جيد بين السلوك المقاس والمحسوب لمجموعات الخوازيق تحت تأثير الأحمال الجانبية باستخدام نموذج مور- كولومب المُعدل في تمثيل التربة.

الكلمات المفتاحية: نموذج التربة، مور- كولومب المُعدل، مور- كولومب، مجموعة الخوازيق، الحمل الجانبي.

1. INTRODUCTION

Normally most of the structures are built using shallow foundations when the upper soil layers are strong enough to resist the applied loads. But in weak soil stratum, the use of deep foundations such as pile groups becomes inevitable. The pile groups can be subjected to lateral loads along with the vertical loads due to; wind forces, earthquakes, landslides, … etc. To study the efficiency of pile groups subjected to lateral loads, it is more important to study the soil-pile interaction. Recently, three-dimensional numerical analysis has become a reliable method in studying geotechnical problems. Numerical studies concerning pile groups and soil-pile interactions are discussed by many researchers [1-4]. Brown et al. [1] found that the pile group efficiency under lateral load is affected by the piles' spacing. Barnsby et al. [٢] found that the pile group's lateral deflection is greater than the lateral deflection of a single pile under the identical loading condition. Mcvay et al. [٣] found that the bending moment of the back-row piles in the pile group is bigger than that of the first (leading) row. Rollins et al. [4] found that increasing the sand's internal friction angle leads to less pile-soil interaction.

Despite the interesting outcomes of these studies, a good agreement with the measured behavior in field was not found due to the complexities of simulating the real behavior of soil. Current research concerning the selection of the constitutive models for soil modeling are complex, many constitutive models have been presented with parameters difficult to estimate. Two widely used constitutive models are the Mohr-Coulomb (MC) and the Modified Mohr-Coulomb (MMC).

The Mohr-Coulomb constitutive model is basically linear (elastic – plastic) constitutive model with uncomplicated parameters to define: internal friction's angle (ϕ), cohesiveness (C), Poisson's ratio (v), and elastic modulus (E) with coulomb's theory of failure criterion.

One of its drawbacks is that the stiffness behavior before failure is assumed to be linear, also the modulus of elasticity is assumed to be constant however, in realistic soil the elastic modulus is a stress-dependent modulus. Mohr-Coulomb model also assumed that the loading and unloading soil stiffness are the same and neglected the confining pressure correlations.

The new Modified Mohr-Coulomb model (MMC) is proposed to overcome the limitations and the disadvantages of the Mohr-Coulomb model (MC) with failure criteria defined by two surfaces; the shear failure surface and the compression failure surface [5] as shown in figure (1), where the Mohr-Coulomb model (MC) has elastic-perfectly plastic stress-strain relationships, and the Modified Mohr-Coulomb model (MMC) has a hyperbolic stress-strain relationship. The soil stiffness in the Modified Mohr-Coulomb (MMC) is stress-dependent while in the Mohr-Coulomb model (MC) the soil stiffness is constant. The Modified Mohr-Coulomb model (MMC) is defined by the same parameters as in the Mohr-Coulomb model in addition to three stress-dependent moduli: primary loading stiffness modulus (E_{50}), the unloading-reloading stiffness modulus (E_{ur}), the oedometer stiffness modulus (E_{oed}) [6,7].

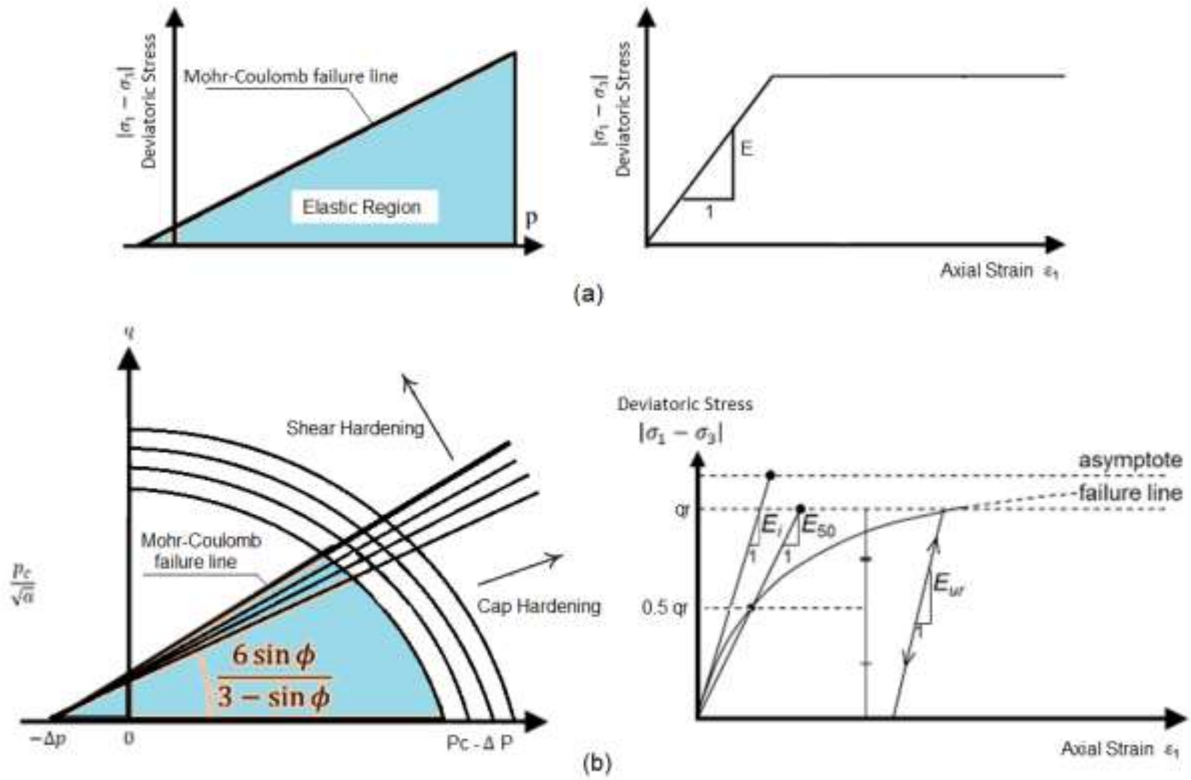


Figure (1) Stress/Strain relationship and yielding conditions of (a) MC (b) MMC models.

In this paper a three-dimensional numerical model of full-scale pile group test is established using two different constitutive models (MC) and (MMC) in defining the soil, to compare the ability of the two constitutive models in capturing the behavior of the pile group and to compare the results with the field measurements.

2. CASE STUDY

Rollins et al [8] performed a lateral load test on a full-scale pile group and single pile to evaluate the behavior of the pile group under lateral load and to compare it with the behavior of the single pile under lateral load. The pile group is a nine-pile group with free-head condition (without pile cap), the arrangement of the piles in the group is in box arrangement with three piles in each row of the three rows (3x3) with spacing between the piles = 3.3 times the pile's diameter center to center as shown in figure (2). The used piles in the pile group test and the single pile test are well-instrumented steel pipe piles with outer diameter = 0.324 m and wall thickness = 0.0095 m (9.5 mm) and a total length of 12.36 m (0.86 m above the ground surface and 11.5 m embedded in the ground) as shown in figure (3).

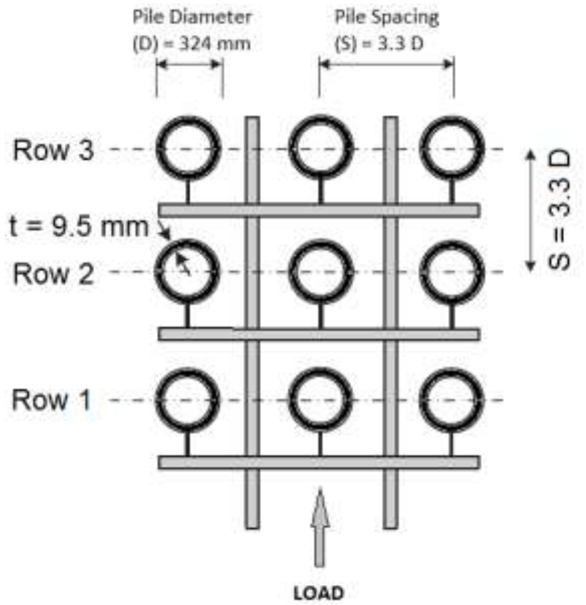


Figure (2) Pile group test plan.

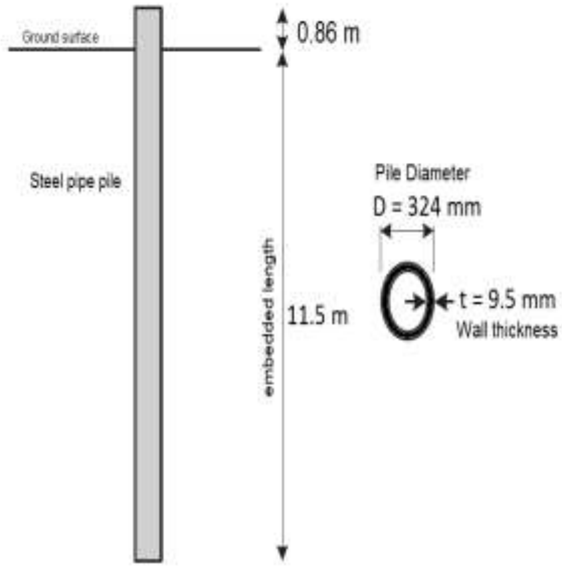


Figure (3) Pile's dimensions.

The tests were conducted in loose fine sand as seen in the soil profile in figure (4). The properties of the soil layers were based on the outcomes of the standard penetration test (SPT) and the cone penetration test (CPT). The soil profile shows that the soil consists of loose fine sand to 6 m depth below the ground surface, the cone resistance (qc) is (6-9) MPa in the top layer and (4-6) MPa below that layer, and the average number of blows in SPT (N) was 10 in the top layer and 7 below that layer.

The lateral load was applied to the single pile through an electric-hydraulic pump at the pile head at 0.86 m height above the ground surface, and to the pile group by an electric-hydraulic pump through a loading frame of rigid beams connected to the piles' head by a pin connection at 0.86 m height above the ground surface to release the rotation of the piles' head.

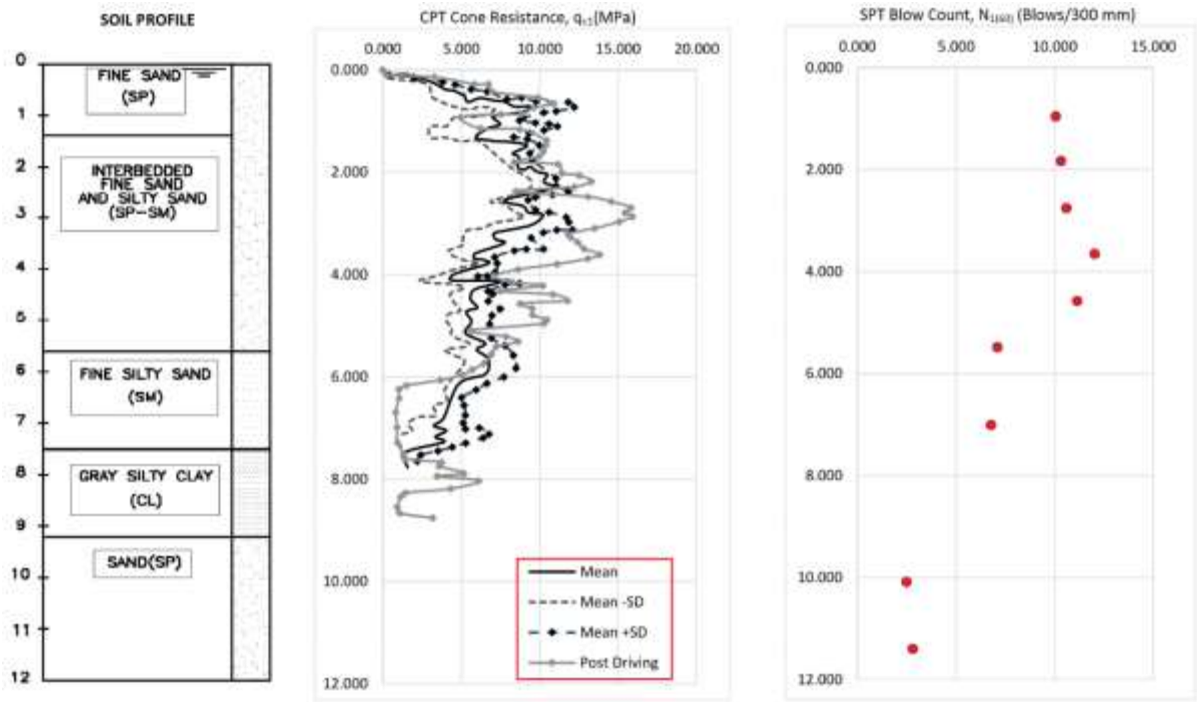


Figure (4) Soil profile, SPT test, and CPT test.

2.1 FIELD MEASUREMENTS

Figure (5) shows the load-deflection curve of the single pile and the average load per pile-deflection curve of the leading, middle, and trailing row of the pile group. As seen in figure (5) the soil stiffness decreases by increasing the applied load, and the deflection of the group's piles is found greater than that of the single pile under the same loading intensity, with the leading row piles resisting more loads than the middle row piles, and the middle row piles resisting more loads than the trailing row piles.

This behavior of the pile group is due to the interaction between the piles in the group, and this interaction increases in the trailing rows because the piles in the trailing rows are subjected to interactions from the adjacent piles in the same row and from the piles in front of them. On the other hand, the leading row piles are only subjected to interactions from the piles in the same row. This interaction effect increases with decreasing the piles spacing in the group (closed-spaced piles) and vice versa.

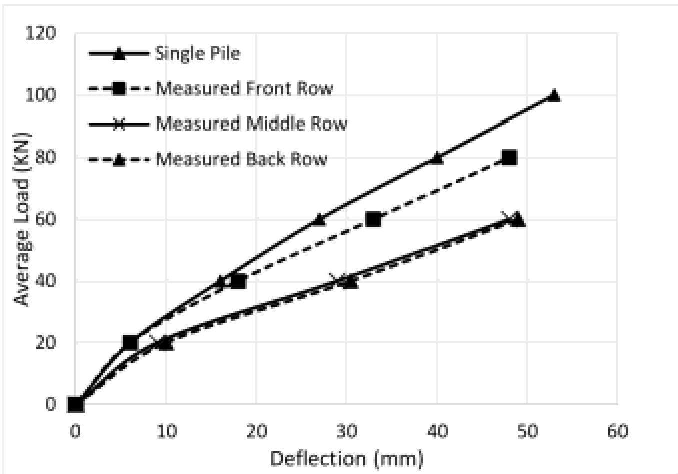


Figure (5) Load-Deflection curve for the single pile and the pile group.

3. NUMERICAL MODELING

The pile group and the single pile are modeled using a three-dimensional finite element software MIDAS GTS-NX. The Mohr-Coulomb (MC) and the Modified Mohr-Coulomb (MMC) constitutive models are used in simulating the soil behavior in the models using the soil parameters in table (1).

Table (1) Soil parameters

Layer	1	2	3	4	5	6	7
Type	Sand	Sand	Sand	Sand	Soft clay	Sand	Sand
Thickness (m.)	0.51	2.08	2.14	2.76	1.76	0.91	1.68
Effe. Unit weight (kn/m^3)	19.5	10.3	10.3	10.3	9.5	10.3	10.3
Cohesion C (kn/m^2)	0	0	0	0	20	0	0
Friction angle ϕ °	33	33	32	30	0	30	30
Poisson's ratio ν	0.3	0.3	0.3	0.3	0.495	0.3	0.3
Triaxial loading stiffness E_{50} (kn/m^2)	12500	12500	12500	11000	11000	9500	9500
Oedometer loading stiffness E_{oed} (kn/m^2)	12500	12500	125000	11000	11000	9500	9500
Triaxial unload. /reload. stiffness E_{ur} (kn/m^2)	62500	62500	62500	55000	55000	47500	47500

The soil's relative density (Dr) is calculated using Kulhawy and Mayne's [9] (Equation 1) based on the SPT results, the angle of internal friction (ϕ) of sand is estimated using the API correlation [10] by (Equation 2), the soil young's modulus is computed using Bowles's [11] (Equation 3)

$$Dr = \left[\frac{(N_1)_{60}}{40}\right]^{0.5} \quad \text{(Equation 1)}$$

$$\phi = 16Dr^2 + 0.17Dr + 28.4 \quad \text{(Equation 2)}$$

where, (ϕ) is the internal friction's angle, and (Dr) is in fraction.

$$E = 500\,(N+15)\ kn/m^2 \quad \text{(Equation 3)}$$

Where, (N) is the SPT blow count

In the Modified Mohr-Coulomb model (MMC), the unloading-reloading stiffness modulus (E_{ur}) is set to be equal 5 times the secant stiffness modulus (E_{50}) which is set equals to the initial modulus, while the oedometer stiffness modulus (E_{oed}) is set equals to the secant stiffness modulus (E_{50}) [12-13].

The piles are modeled as linear-elastic materials with unit weight 78 kn/m^3, Poisson's ratio 0.3, and modulus of elasticity 210,000 MPa. Mesh elements (tetrahedra) are used in modeling the soil layers with different mesh sizes to study the effect of each mesh size on the analysis results. It is found that the optimum mesh size is (0.1m) for the pile shell elements and the soil around the piles and the mesh size increases gradually until reaches (1m) at the outer edges of the model as shown in figure (6).

These outer edges are restrained to prevent any numerical instability in the analysis. In the upward direction, the side edges are free to move, however in the lateral direction, they are fixed. The bottom edge is fixed, and the top edge is free. Different models with different spacing between the outer edges and the pile group are studied. It is found that setting the outer edges at 10 times the pile's diameter far from the pile group in x and y direction, and at 6 times the pile's diameter in z-direction does not affect the stresses generated from the laterally loaded piles.

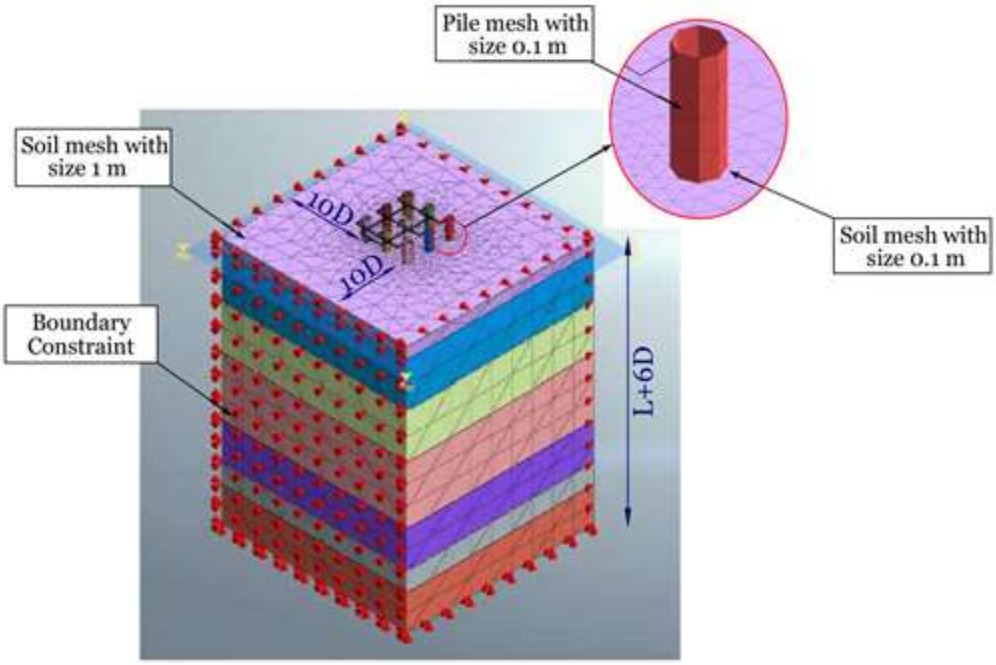


Figure (6) Model characteristics

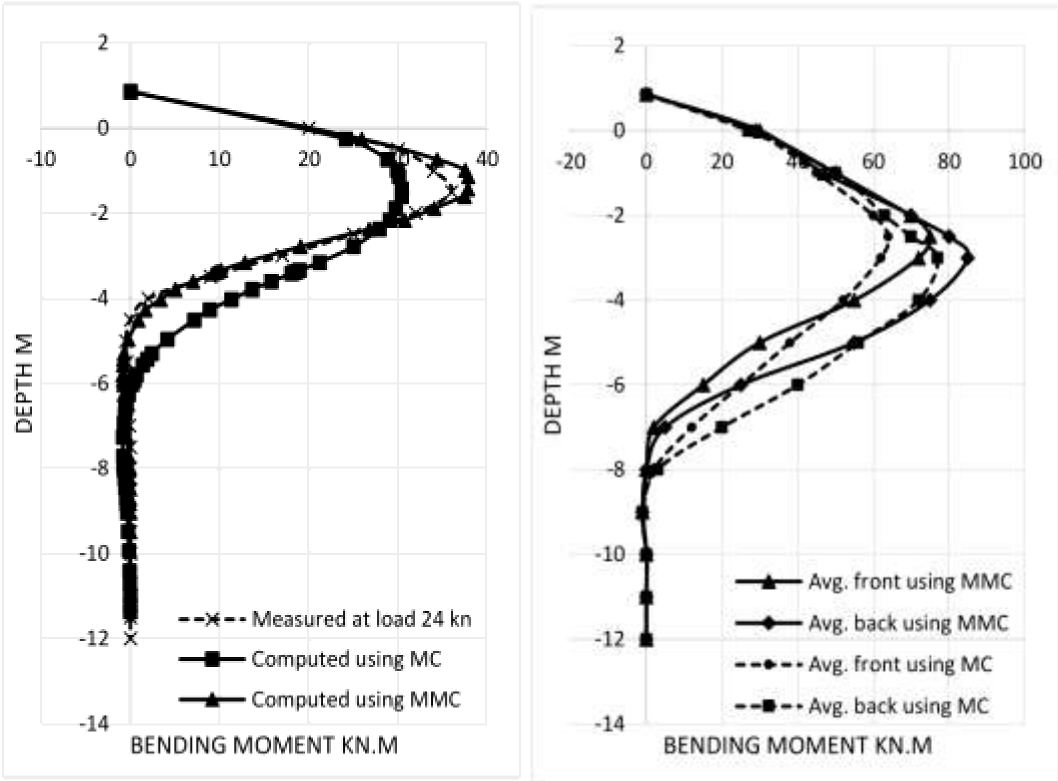
4. RESULTS AND DISCUSSION

Figure (8) shows the load-deflection curve of the single pile and the pile group using two different constitutive models: Mohr-Coulomb (MC) and Modified Mohr-Coulomb (MMC) models for soil. The pile group deflection is bigger than the deflection of the single pile under the same average load per pile, and the leading row piles in the group resist more load than the trailing row piles. Table (2) compares the measured deflection behavior and the computed deflection behavior using two different constitutive models.

A good agreement is observed between the measured deflection and bending moment and the computed deflection and bending moment using the modified Mohr-Coulomb model (MMC) in soil modeling than using the Mohr-Coulomb model (MC). The Mohr-Coulomb model (MC) underestimated the deflection for both the single pile and the pile group and underestimated the maximum bending moment. However, it overestimated the bending moment beneath the max. bending moment. The computed (in this study) maximum bending moment in the single pile, using the MC model is 83% of the measured maximum bending moment while the computed maximum bending moment using the MMC model is 105% the measured maximum bending moment. For the first row in the pile group, the computed maximum bending moment using the MC model is 10% less than the computed maximum bending moment using the MMC model and for the trailing rows in the pile group, the computed maximum bending moment using the MC model is 8% less than the computed maximum bending moment using the MMC model.

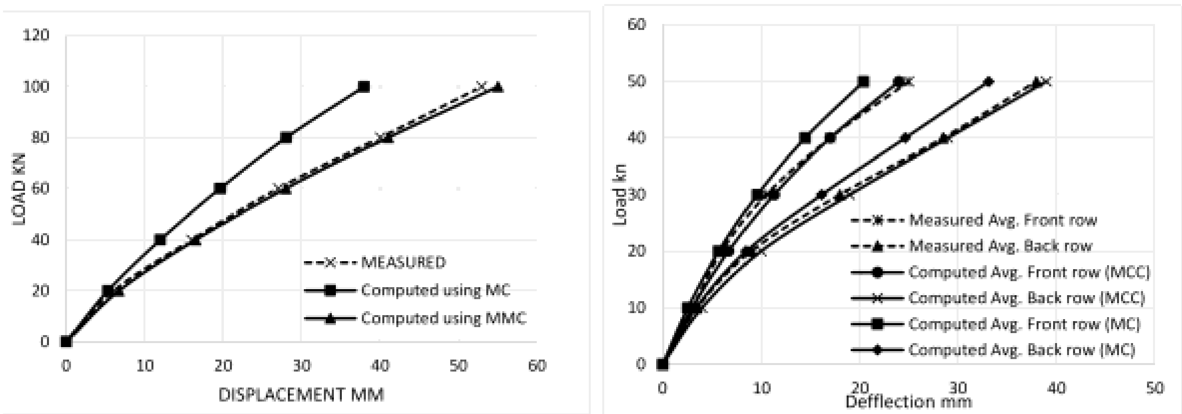
Table (2) Computed deflection behavior of single pile and pile group using MC and MMC models as a percentage of the measured deflection behavior

	Single pile	First row piles in the pile group	Trailing rows piles in the pile group
(MC) model	75%	87%	91%
(MMC) model	104%	103%	104%



(a) (b)

Figure (7) Bending moment vs depth for (a) single pile at load 24 KN and (b) front and back row piles in pile group at load 48 KN



(a) (b)

Figure (8) Load vs deflection curve for (a) single pile and (b) front and back row piles in pile group.

5. CONCLUSIONS

Based on the analysis study the following are concluded:

- A good agreement between the computed behavior of the pile group using the Modified

Mohr-Coulomb model (MMC) in modeling the soil and the measured behavior.

- The lateral deflection of the pile group is bigger than that of the single pile under the same average load per pile.
- The piles in the leading row of the pile group resist less load than the single pile but more load than the piles in the trailing rows.
- The Modified Mohr-Coulomb model (MMC) can define the realistic behavior of sand and capturing the real behavior of pile groups under lateral loads.

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