Numerical Analysis of Jet Grouting Strengthened Pile under Lateral Loading

Reza Ziaie Moayed, Naeem Gholampoor

***Abstract*—**Jet grouting strengthened pile (JPP) is one of composite piles used in soft ground improvement. It may improve the vertical and lateral bearing capacity effectively and it has been practically used in a considerable scale. In order to make a further research on load transfer mechanism of single JPP with and without cap under lateral loads, JPP is analyzed by means of FEM analysis. It is resulted that the JPP pile could improve lateral bearing capacity by compared with bored concrete pile which is higher for shorter pile and the biggest bending moment of JPP pile is located in the depth of around 48% of embedded length of the pile. Meanwhile, increase of JPP pile length causes to increase of peak mobilized bending moment. Also, by cap addition, JPP piles will have a much higher lateral bearing capacity and increasing in cohesion of soil layer resulted to increase of lateral bearing capacity of JPP pile. In addition, the numerical results basically coincide with the experimental results presented by other researchers.

***Keywords*—**Bending moment, FEM analysis, JPP pile, lateral bearing capacity.

I. Introduction

THE use of concrete pile because of its low cost and large side surface area which can provide high lateral friction has been developed in a wide range of civil projects. However, often before pile being crushed, pile friction resistance has emerged into full play. To overcome on this behavior, Jet Grouting pile [1] (referred to as JPP) can be used.

JPP pile is a composite pile which made of a concrete core pile embedded in a high pressure jet grouting cement –soil mixture. Therefore, JPP contains two parts of high pressure rotary get grout and core pile with high strength. Previous studies performed by other researchers shows the beneficial effect of jet grouting of concrete piles on improvement of pile vertical bearing capacity by means physical modeling, numerical analysis, simplified calculation method and variational approach. Reference [2] performed further research on load transfer mechanism of single JPP with cap and resulted that compared with single JPP, JPP with cap has larger bearing capacity and the ratio of load carried by cap is higher. Also, the cap of JPP makes friction resistance decrease and tip resistance increase. The results of numerical analyses and simplified calculation method performed by [3] and [4] based on field load test show that unconfined compressive strength of soil-cement should be no less than 1.5 MPa and the thickness of soil-cement should be not only no less than 100 mm. Comparisons between results using practical variational method by [5] and model test measurements indicate that the method can predict the performance of single JPP pile and the load-settlement ratio is hardly affected by Young's modulus of soil-cement pile, thus the behavior of JPP pile is controlled by the core pile. The results obtained based on the simplified calculation method presented by [6] show that the sub-combination JPP pile has better carrying effect and should be adopted in actual construction and also, soil-cement elastic modulus has small effect on axial bearing properties of JPP, but should meet structural requirements. As known, these piles are subjected to lateral loads in addition to vertical loads. But, the number of studies about the behavior of JPPs under lateral loading is at least in comparison of vertical loading. Reference [7] performed large-scale tests to evaluate the behavior of single JPP pile under lateral loading. The results showed that the JPP pile could improve horizontal bearing capacity by about 15% compared with bored concrete pile and the biggest bending moment of JPP pile is located in the place 2 m below the pile tip.

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Due to lack of numerical investigations about behavior of JPP pile under lateral loading, this paper aims to investigate the behavior of single JPP pile under lateral loading in comparison with bored concrete pile by means of FEM analyses. Also, obtained results are compared with results of large-scale tests presented by [7].

II. Numerical Analyses

All of the numerical analyses in this section were carried out in three-dimensional space using the finite element program ABAQUS. In order to evaluate the validity of FE analysis method used in this paper, a large scale test simulated with same characteristics as performed by [7]. The model consisted of a 5 m depth concrete core pile with diameter of 30 cm embedded in a high pressure jet grouting soilcrete with thickness of 10cm placed in a layered soil mass of $4×5×7$ m^3. As shown in Fig. 1, the mass soil consisted of two layers. The upper layer is silty clay with thickness of 3 m and the bottom is a sandy soil with 4 m thickness.

A ramped lateral load up to 85 kN was applied on depth of 50 cm from top of JPP to investigate the lateral load carrying capacity of JPP piles. In the case of JPP with cap the lateral load applied through the concrete cap with dimensions of $1.5×1.5×0.4$ m^3.

For modeling the behavior of soilcrete and soil layers, the Mohr-coulomb plasticity model was used which have linearly elastic perfectly plastic behavior. Also, concrete core pile has been modeled as a liner elastic material. The material properties selected in the analyses were based on the samewhich have been used by [7] and are presented in Table I.

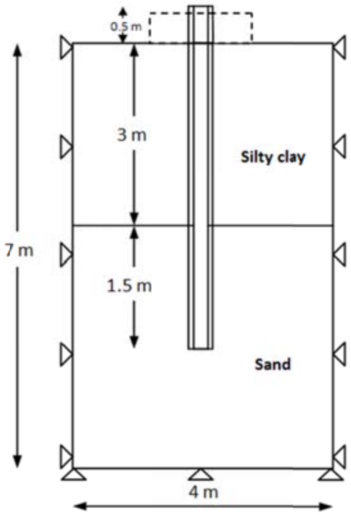

Fig. 1 Schematic view of numerical model

As shown in Fig. 2, the finite element mesh used in the numerical simulations was developed using 6-node linear triangular prism elements for soil massand core pile and 8-node linear brick for soilcrete.

TABLE I
MATERIAL PROPERTIES USED IN NUMERICAL MODEL

Material	γ(kN/m^3)	E (KPA)	C (KPA)	Φ (º)	ψ (º)	υ
Sandy soil	15.50	36000	9.76	24.3	16	0.35
Silty clay	19.20	14000	24.7	28.2	0	0.40
Sand-Cement	-	2.19×10^6	-	-	-	0.40
Silty clay-Cement	-	0.9×10^6	-	-	-	0.35
Concrete (C25)	2400	21×10^6	-	-	-	0.30

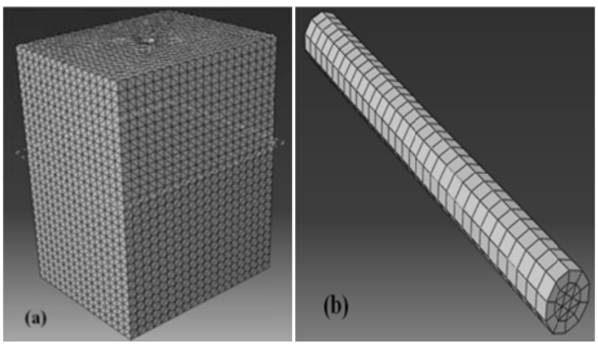

Fig. 2 Typical finite element mesh used for (a) soil mass and (b) JPP

III. RESULTS AND DISCUSSION

A. Lateral Bearing Capacity

Fig. 3 shows the lateral load-displacement curves of 5 m length bored concrete pile and JPP without cap from FEM analyses in comparison with large-scale test results presented by [7]. As shown in the figure, lateral bearing capacity of 5 m length JPP and bored concrete piles without cap is 72 and 63kN, respectively. In other words, using JPP piles can improve lateral bearing capacity up to around 15% of the same for bored concrete pile. Also, comparison between results of FEM and large-scale tests performed by [7] shows good correspondence of them.The existent trifle disparity is because of the material homogeneity assumed by numerical analysis and also, different between position of tested piles in FEM analyses and large-scale test performed by [7].

As indicated in Fig. 4, by increasing the pile length from 5 to 7 m the lateral bearing capacity of JPP and bored concrete pile without cap increases to around 22% and 29% of lateral bearing capacity of 5 m length piles, respectively. This is because of excess passive resistance mobilized on increased embedded length of the piles. Also, improvement of lateral bearing capacity of 7 m length bored concrete pile by jet grouting is around 9% which is less than same for 5 m length piles.

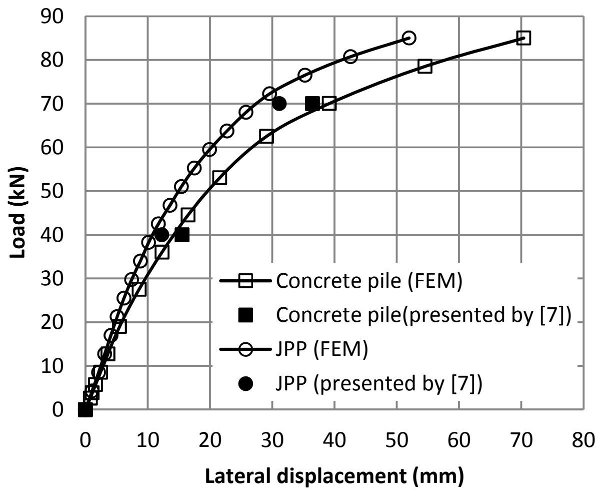

Fig. 3 Lateral load-displacement curves for 5 m length bored concrete pile and JPP without cap

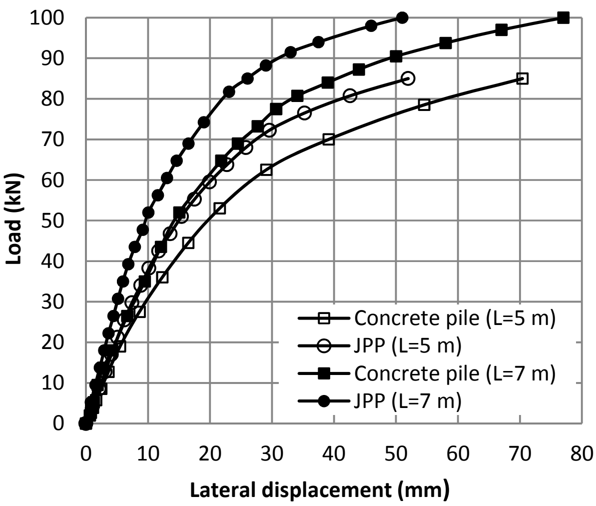

Fig. 4 Lateral load-displacement behavior for considered piles

B. Bending Moment

Fig. 5 shows the variation of bending moment in depth of JPP piles with length of 5 and 7 m under different lateral loads.

The results show that the bending moment along the JPP pile with different length firstly increases to reach its maximum value and then decreases, but the symbol remains unchanged which indicate that no change in tension and compression characteristics with depth is occurred. It is obvious in the figure that, under loads less than around 42 kN for JPP with length of 5 m and 56 kN for 7 m length, by increasing of lateral load, bending moment increases gradually and while the load exceeds 42 kN and 56 kN, the bending moment increases rapidly which causes propagation of cracks in the JPP pile.

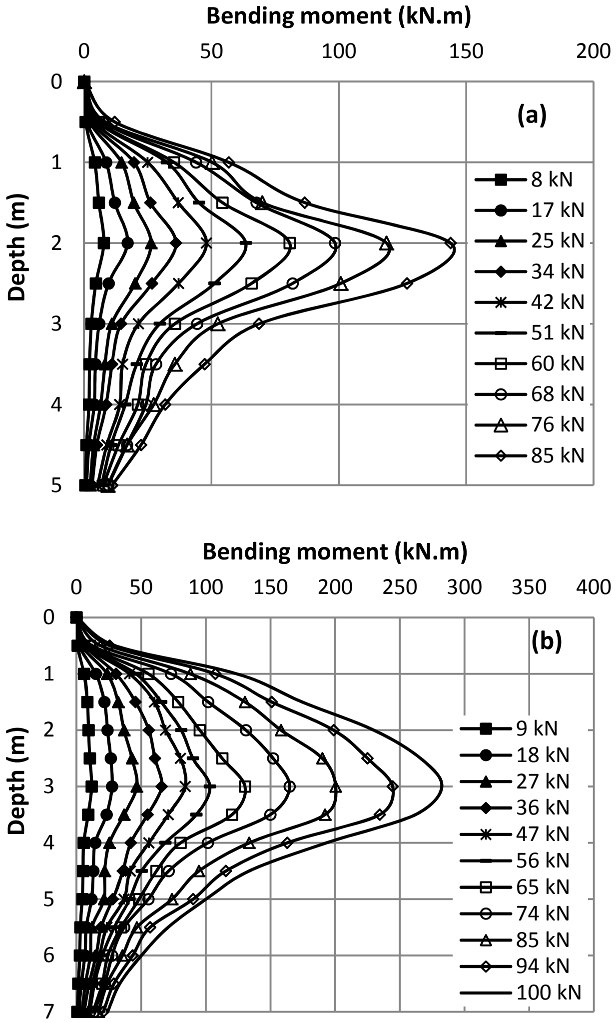

Fig. 5 Bending moments of JPP with length of (a) 5 m and (b) 7 m under different loads

Also, it can be seen in Fig. 5 that the peak mobilized bending moment for JPP with length of 7 m is more higher than same for 5 m length but, for both lengths of JPP in the loading process, the position of maximum bending along JPP pile almost is remained constant and is around the depth of 48% of embedded length of the pile, which is in accordance with large-scale test results by [7].

C. Effect of Soil Layering on Lateral Bearing Capacity

In order to investigate the effect of soil layering and cohesion of soil on the lateral bearing capacity of JPP pile, JPP with length of 5 m subjected to lateral load in a clay layer with different cohesion in addition to two layer soil considered previously.

As shown in Fig. 6, by changing the soil layers from two layer (Sand-Silty clay) to single layer (Silty clay) with the same cohesion the lateral bearing capacity increased up to around 18%. This is because of increasing in passive forces against lateral movement of JPP caused by increase of soil cohesion resulted from replacing sand layer with silty clay. From figure, this is obvious that after reaching bearing capacity, the increasing ratio of lateral displacement for JPP embedded in silty clay layer increased in comparison with two layer soil.Since, the elastic modulus and consequently stiffness of silty clay-cement is less than the same for sand-cement jet grout. Also, by increase of cohesion of soil layer from 147 kPa to 34.7 kPa, the lateral bearing capacity of JPP pile increased from 76 kN to 94 kN, which is because of increasing in passive forces against lateral displacement of JPP pile.

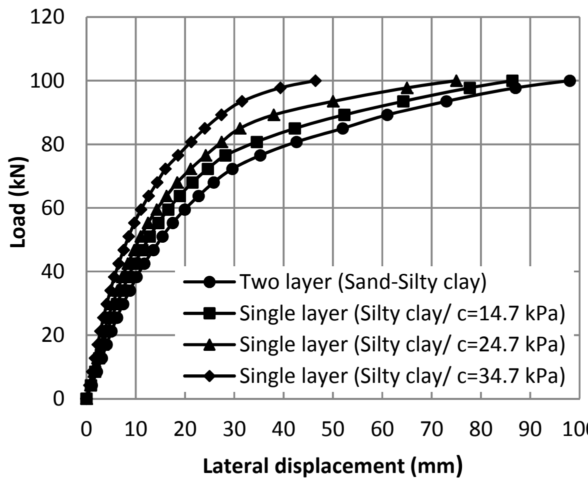

Fig. 6 Lateral load-displacement behavior for 5 m length JPP pile embedded in various soil layers

D. Effect of Cap on Lateral Bearing Capacity of JPP

As shown in Fig. 7, by cap addition, lateral bearing capacity of JPP pile significantly increases. This is because of increasing in contact surface of pile-soil and increasing the weight of JPP pile which causes increase of friction resistance. So, the lateral displacement of JPP pile with cap has been significantly controlled. Also, comparison of FEM and large-scale test results shows validity of FEM results.

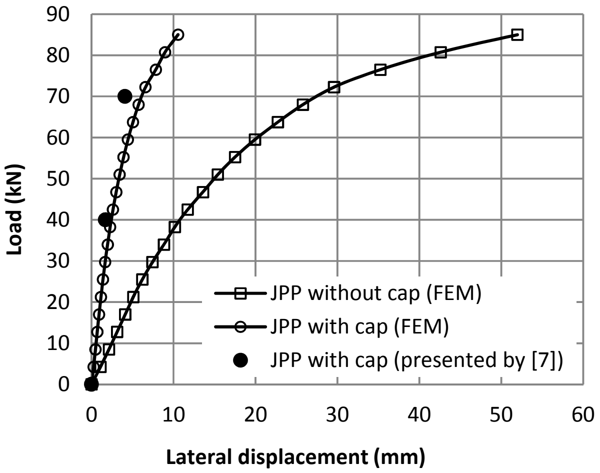

Fig. 7 Lateral load-displacement curves for 5 m length JPP pile with and without cap

IV. Conclusion

The lateral behavior of JPP and bored concrete piles with and without cap investigated through the FEM analyses. The obtained results are as follow:

- Using JPP piles can improve lateral bearing capacity up to around 15% and 9% of the same for 5 m and 7 mbored concrete piles.
- At the range of small loads, by increasing of lateral load, bending moment increases gradually and while the load exceeds to greater loads, the bending moment increases rapidly which causes propagation of cracks in the JPP pile.
- By increasing the length of JPP pile the peak mobilized bending moment increases.
- For both lengths of JPP, the position of maximum bending along JPP pile is around the depth of 48% of embedded length of the pile.
- By increase of cohesion of soil layer, the lateral bearing capacity of JPP pile increased because of increasing in passive forces against lateral displacement of JPP pile
- By cap addition, lateral bearing capacity of JPP pile significantly increases and lateral displacement has been controlled.
- Comparison of FEM and large-scale test results shows validity of FEM results.

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