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# Numerical Evaluation of Lateral Bearing Capacity of Piles in Cement-Treated Soils

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***Abstract*—**Soft soil is used in many of civil engineering projects like coastal, marine and road projects. Because of low shear strength and stiffness of soft soils, large settlement and low bearing capacity will occur under superstructure loads. This will make the civil engineering activities more difficult and costlier. In the case of soft soils, improvement is a suitable method to increase the shear strength and stiffness for engineering purposes. In recent years, the artificial cementation of soil by cement and lime has been extensively used for soft soil improvement. Cement stabilization is a well-established technique for improving soft soils. Artificial cementation increases the shear strength and hardness of the natural soils. On the other hand, in soft soils, the use of piles to transfer loads to the depths of ground is usual. By using cement treated soil around the piles, high bearing capacity and low settlement in piles can be achieved. In the present study, lateral bearing capacity of short piles in cemented soils is investigated by numerical approach. For this purpose, three dimensional (3D) finite difference software, FLAC 3D is used. Cement treated soil has a strain hardening-softening behavior, because of breaking of bonds between cement agent and soil particle. To simulate such behavior, strain hardening-softening soil constitutive model is used for cement treated soft soil. Additionally, conventional elastic-plastic Mohr Coulomb constitutive model and linear elastic model are used for stress-strain behavior of natural soils and pile. To determine the parameters of constitutive models and also for verification of numerical model, the results of available triaxial laboratory tests on and insitu loading of piles in cement treated soft soil are used. Different parameters are considered in parametric study to determine the effective parameters on the bearing of the piles on cemented treated soils. In the present paper, the effect of various length and height of the artificial cemented area, different diameter and length of the pile and the properties of the materials are studied. Also, the effect of choosing a constitutive model for cemented treated soils in the bearing capacity of the pile is investigated.

***Keywords*—**Cement-treated soils, pile, lateral capacity, FLAC 3D.

## I. Introduction

SOFT soils have low shear strength and stiffness that makes engineering activities on them cumbersome. Low bearing capacity and high immediate and consolidation settlements are some problems associated with these soils that make ground stabilization and improvement imperative [1]. Stabilization of these soils improves their stiffness and resistance. Traditional ground improvement methods like soil replacement and use of geotextiles that are employed for so many years, have high cost and need long construction time [2]. In recent decades, a new technique, chemical soil stabilization, has been developed [3]. In this technique, soil with poor engineering properties is mixed with some stabilizers and as a result of some chemical reactions like pozzolanic reaction and carbonation, its strength parameters improve. Among pozzolans, cement due to its low cost and a higher rate of strength increase is more widely used compared to other stabilizers like lime [4].

In soft soils, piles are commonly used to transfer loads to higher depths to control settlement and attain allowable load bearing capacity. However, the capacity of piles to resist large lateral loads like in offshore structures is also important [5]. In order to improve the structural response in soft soils, the surrounding ground could be improved. So far, many methods for estimation of bearing capacity of piles have been developed, but the bearing capacity of piles in improved soils has not been thoroughly investigated [6], [7]. Use of conventional methods to determine the bearing capacity in improved soils is not possible due to inhomogeneity of surrounding soil. The response of the system in this condition is a function of characteristics of pile and properties of undisturbed and improved soil. In this paper, the bearing capacity of piles in cement-improved soil is studied. First, the constitutive parameters of undisturbed and improved soil are estimated using the results presented by Faro et al. [8]. Then, the numerical model is verified against the in situ lateral loading of a pile. Finally, a sensitivity analysis is done on the parameters of the constitutive model, the length of the pile and its radius.

## II. Material Properties

Faro et al. presented the results of a series of in situ tests for measurement of the lateral load-bearing capacity of a pile group in cement improved soil [8]. The undisturbed soil is categorized as CL according to the unified classification system. The soil that is the result of in situ weathering of bedrock has a specific gravity of 15.8 kN/m$^3$. To determine other properties of undisturbed soil, triaxial CD test is undertaken on the cylindrical specimens with the radius of 50 mm and height to radius ratio of 2. Three confining pressures of 20.60 and 100 kPa were applied on the samples. Based on the results of the tests, the internal friction angle and the cohesion are estimated to be 31.8° and 23.8 kPa, respectively.

The cemented soil is produced from a mixture of fine-grained sandy soil with cement equivalent of 7% by weight of dry sand. The produced cemented soil is used in 100 mm layers around the piles after the removal of undisturbed topsoil. The specific gravity of cemented soil is 17.6 kN/m$^3$, and its unconfined compressive strength is 1 MPa after 14

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days of curing. Triaxial CD tests are also performed on three samples of produced cemented soil under the confining pressures of 20, 200, and 400 kPa. Based on the tests results, the internal friction angle and the cohesion of the peak strength are estimated as 38.3° and 346 kPa, respectively.

To determine other parameters of the constitutive model, the conducted triaxial tests on undisturbed soil and the cemented soil are modelled using FLAC 3D software [9]. The results of the simulations with experimental results are shown in Figs. 1 and 2 for undisturbed soil and the cemented soil, respectively. The points show the experimental results while lines represent the numerical model results. Constitutive model parameters are given in Table I. Considering hardening behavior of undisturbed soil, the strain softening/hardening constitutive model in the software is used to simulate the soil behavior. The cemented soil shows strain softening due to breakage of the cementation between the grains. The elastoplastic Mohr-Coulomb model could not be used to simulate this behavior; therefore, the strain softening/ hardening constitutive model is also used for the cemented soil. In this model, it is possible to change the strength parameters of the soil with plastic strain. Therefore, the softening of cemented soil or the hardening of undisturbed soil could be well modelled. When the plastic strain increases, the peak strength parameters of the soil decrease to reach their ultimate state. The peak and ultimate strength parameters of the soil are given in Table I.

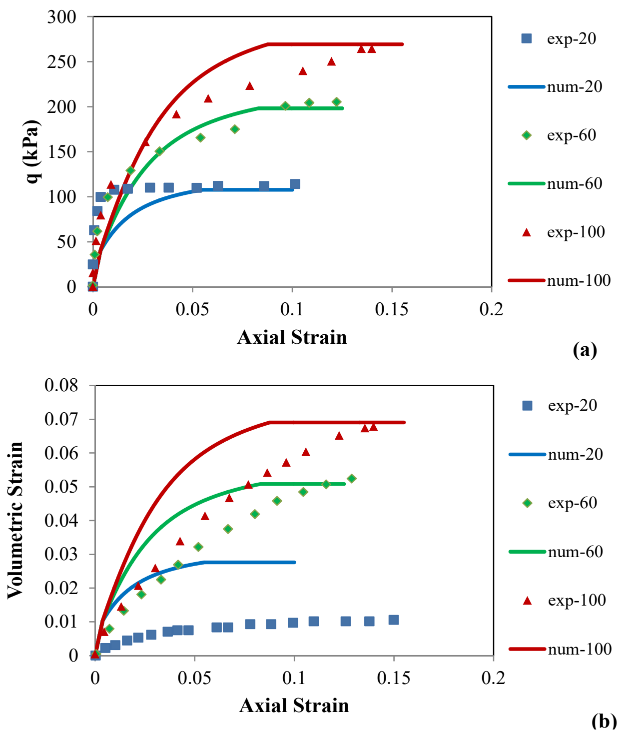


Fig. 1 Experimental results and numerical modeling of triaxial test on natural soil (a) Deviatoric stress stress-Axial strain, (b) Volumetric strain-Axial strain[8]

It is observed in Fig. 1 that the experimental and numerical curves of volumetric and axial strains are not matched in initial parts. It might be due to some problems in measurement systems as well as some weaknesses on the constitutive model, but since here the aim is just investigation on the bearing capacity and not displacement, the observed inconsistency is irrelevant. For the cemented soil on the 400 kPa confining pressure, it is observed that the soil first contracts, then dilates and at last contracts again. As dilation always happens after contraction, the observed behavior might happen as a result of some problems with the test.

TABLE I
NATURAL SOIL AND CEMENTED SOIL CONSTITUTIVE MODEL PROPERTIES

| Material | Natural Soil | Cemented Soil |
|---|---|---|
| Density $(\frac{kN}{m^3})$ | 15.8 | 17.6 |
| Peak Friction Angel (deg) | 31.8 | 38.3 |
| Peak Cohesion (kPa) | 23.8 | 346 |
| Residual Friction Angel (deg) | 31.8 | 31 |
| Residual Cohesion | 23.8 | 55 |
| Young Modulus (kPa) | 7500 | 230000 |
| Poisson Ratio | 0.3 | 0.3 |

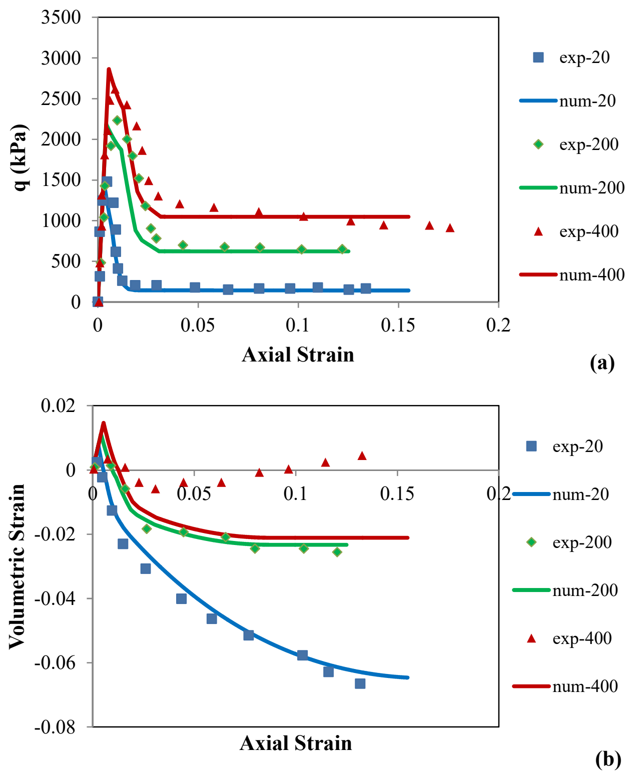


Fig. 2 Experimental results and numerical modeling of triaxial test on natural soil a)- Deviatoric stress stress-Axial strain b)-Volumetric strain-Axial strain [8]

## III. NUMERICAL MODELLING

### *A. Verification*

For verification and validation of the numerical model, the results of in situ tests of Faro et al are used. They laterally loaded some piles of D=0.6m and L=3m on a double-layered system formed by an artificially cemented compacted topsoil layer. The properties of undisturbed and cemented soil were given in the previous section. Fig. 3 shows a schematic cross-section of test whereabouts. The cemented radius surrounding the pile ( $D_{cem}$ ) is two to four times of the diameter of the pile and the height of improvement ( $L_{cem}$ ) is 0.1 to 0.3 times of pile length. The geometry of the model for one of the modes is shown in Fig. 4. Given the model symmetry, only half of the geometry is modelled.

The mesh is refined near the pile to increase the modelling accuracy. The height of the numerical model is 1.5 times the pile length and its width are 4 times of pile length. Since the plastic points did not cut the model boundaries while the load combinations are applied, the model dimensions seem to be proper. The bearing capacities of the experiments as well as numerical models are given in Table II. As observed, in all circumstances the difference of numerical model and in situ tests are low, therefore materials parameters, as well as the process of numerical modelling, seem to be accurate and appropriate.

In both cases of numerical modelling and in situ tests, cementation of the surrounding soil even at low volumes (0.1L and 2D), significantly increases lateral bearing capacity. As dimensions of cemented area increases, due to the higher strength and stiffness of the cemented area, lateral bearing capacity also increases. Based on the results, the highest increase in stiffness is observed for the cementation height and radius of 0.2L to 0.3L and 4D, respectively.

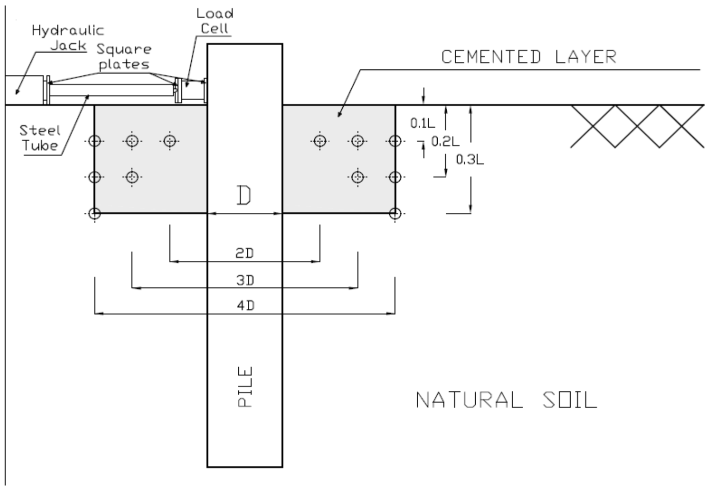


Fig. 3 Schematic view of insitu tests [8]

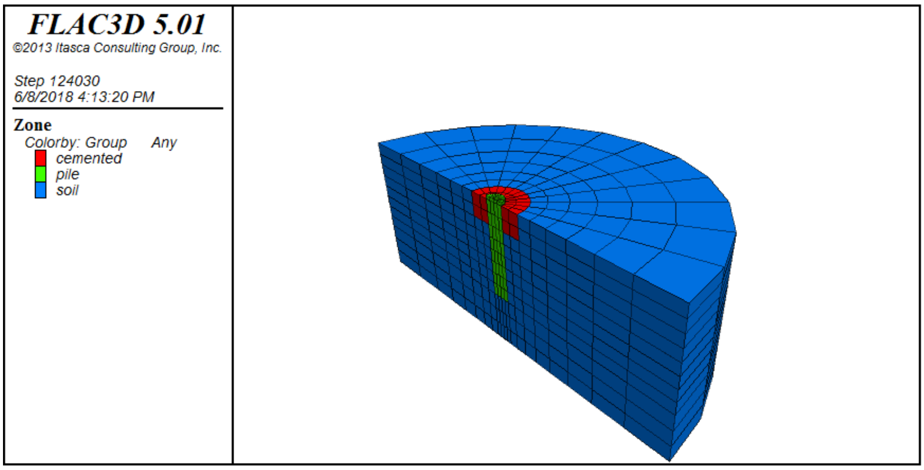


Fig. 4 The geometry of the numerical model

*B. The Effect of Pile Diameter*

Based on the results of the previous section, the following values are assumed for model parameters:

The results of the analysis are shown in Fig 5. As the pile diameter increases, lateral bearing capacity grows. Part of this growth is due to the increase of pile diameter and another part is due to the increase of cementation radius. Since the proportion of cemented area to the pile diameter is considered constant (equal to 4), expansion of the pile diameter leads to the expansion of the cemented area. An increase of 20 cm in pile diameter from 40 cm to 60 cm and from 60 cm to 80 cm leads to 54% and 30% growth in lateral bearing capacity, respectively. Therefore, the increase of lateral bearing capacity in lower radius is more significant. As it could also be seen in

Fig 5, the slope of lateral bearing capacity reduces in larger diameters.

TABLE II
PILE BEARING CAPACITY IN SITU TESTING AND NUMERICAL ANALYSIS

| Notation | $L_{cem}/L$ | $D_{cem}/D$ | $H_{ult}$ $(kN)$ exp | $H_{ult}$ $(kN)$ num |
|---|---|---|---|---|
| Nat-D0.6-L3 | - | - | 80 | 84 |
| Cem-2D-0.1L | 0.1 | 2 | 140 | 145 |
| Cem-3D-0.1L | 0.1 | 3 | 160 | 163 |
| Cem-3D-0.2L | 0.2 | 3 | 220 | 210 |
| Cem-4D-0.1L | 0.1 | 4 | 150 | 170 |
| Cem-4D-0.2L | 0.2 | 4 | 250 | 244 |
| Cem-4D-0.3L | 0.3 | 4 | 250 | 247 |

The modal displacement of two piles with the diameter of 80 cm and 40 cm is shown in Fig. 6. In the diameter of 80 cm, pile rotated like a rigid body under the horizontal load while in the diameter of 40 cm, the pile has a curvature and part of pile length has a smaller displacement. The inflexion point is at the 50 % of pile length. The modal displacement indicates that the pile with the diameter of 40 cm behaves like a short pile, while pile with the 80 cm diameter behaves like a long pile. Considering the ratio of length to diameter of 7.5 and 3.75 in the two cases, this behavior is consistent with the classification of long and short piles in previous studies [8], [10], [11].

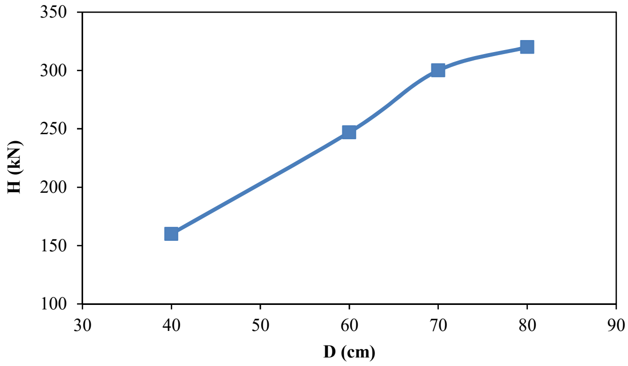


Fig. 5 Evaluation of lateral bearing capacity of piles with pile diameter

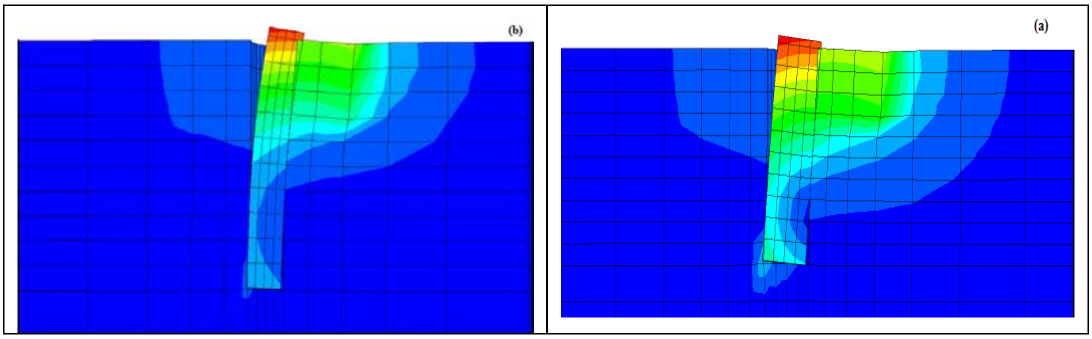


Fig. 6 Deformation mode of pile under horizontal loading a)-D=80 cm b)-D=40 cm

*C. Effect of Pile Length*

In the analysis of this section, the following values are considered:

The results of the analysis are shown in Fig. 7. As the pile length increases, lateral bearing capacity also grows. Part of this growth is due to increase of pile length and another part is due to the increase in height of the surrounding cemented area. A 66% increase in pile height leads to roughly 10% increase in lateral bearing capacity. This increase is smaller compared to the effect of pile diameter that shows the greater impact of pile diameter on lateral bearing capacity.

The modal displacement of two piles with the diameter of 3 and 5 meters are shown in Fig. 8. Pile with a 3m length has the length to diameter ratio of 5 and rotates like a rigid body under lateral load. Pile with 5 m length has the length to diameter ratio of 8.33 and has a curvature and part of the pile length has a smaller displacement. The inflexion point is at the 50% of pile length. The modal displacement indicates that piles with the length of 3 m and 5 m behave like short and long piles. This behaviour is consistent with the classification of long and short piles in previous studies [8], [10], [11]..

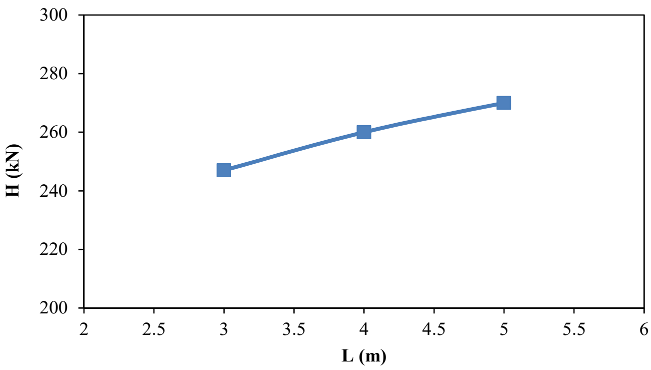


Fig. 7 Evalution of lateral bearing capacity of piles with pile length

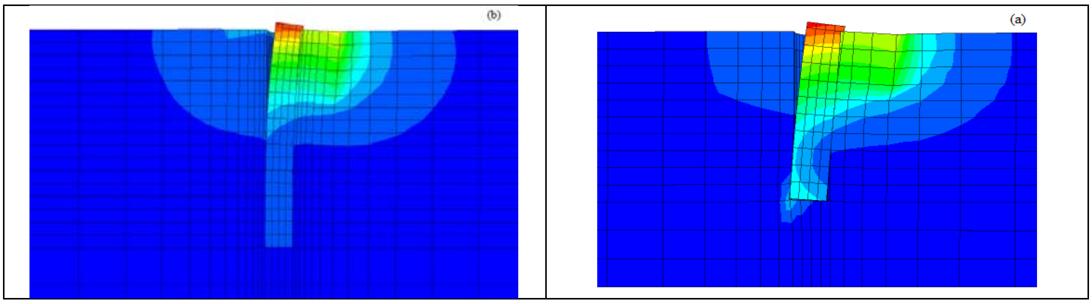


Fig. 8 Deformation mode of pile under horizontal loading a)-L=3 m b)-L=5 m

### *D. Effect of Constitutive Model*

In this study, the strain softening/hardening model is used to model the stress-strain behavior of undisturbed and artificial cemented soil. The use of such a model, in particular for artificially cemented soil that shows strain softening is essential. However, due to simplicity and applicability of Mohr-Coulomb model and since in use of Mohr-Coulomb model it is not necessary to determine how strength parameters evolve with plastic strain, the effect of its use to determine the ultimate bearing capacity of the pile in the cemented ground is investigated. In this regard, the strength parameters of undisturbed and cemented soil are considered equal to the ultimate values presented in Table I and the first, fourth and seventh analysis in Table II are repeated with Mohr-Coulomb model. The results of the analysis with Mohr-Coulomb and reference model are given in Table III. It is observed that two models give the same results if the cemented soil is not considered, but by considering the surrounding cemented soil, the results become different.

Comparison of the results shows that when the surrounding cemented area increases, the difference between the results of strain softening/hardening model with the Mohr-Coulomb model become more. Considering the hardening behavior of undisturbed soil, strain softening is not observed and the strength of the soil remains constant after its peak strength. For the cemented soil, as mentioned, strain softening is observed that means the reduction of strength parameters after peak strength. In this condition, the use of a constitutive model like the Mohr-Coulomb model that has constant strength parameters is not justified.

The comparison of modal deformation for two constitutive models shows that the deformation of the pile is not dependent on the constitutive model and in all cases mentioned in Table III, pile rotates like a short pile. Therefore, the modal deformations are not presented.

TABLE III
EVOLUTION OF LATERAL BEARING CAPACITY OF PILES WITH SOIL CONSTITUTIVE MODEL

| Notation | $H_{ult}$ (kN) ST* | $H_{ult}$ (kN) MC** | Differences (%) |
|---|---|---|---|
| Nat-D0.6-L3 | 84 | 84 | 0 |
| Cem-3D-0.2L | 210 | 160 | -23.8 |
| Cem-4D-0.3L | 247 | 182 | -26.3 |

** = Strain Softening / Hardening Constitutive Model*

*** = Mohr Coulomb Constitutive Model*

## IV. CONCLUSIONS

In this paper, the effect of ground improvement in surrounding of piles on the bearing capacity is investigated. Cement improvement is considered and the effect of various parameters on the lateral bearing capacity of the pile is investigated. It is observed that by the growth of improved surroundings, the lateral bearing capacity of soil significantly rises. There is an optimum limit for dimensions of the cemented area. The increase of the diameter of piles with lower cross sections has more effects on the lateral bearing capacity. The pile diameter has more effect on lateral bearing capacity than the length of the pile. Finally, it is observed that in cemented grounds, use of a strain softening/hardening model is essential and elastoplastic models like Mohr-Coulomb could not represent the real soil behavior.

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