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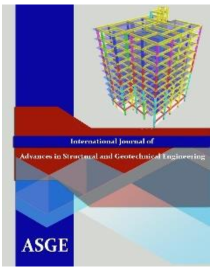

International Journal of Advances in Structural and Geotechnical Engineering

https://asge.journals.ekb.eg/

Print ISSN 2785-9509 _Online ISSN 2812-5142_

Special Issue for ICASGE'19

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ASGE Vol. 03 (02), pp. 1-13, 2019

Improving Lateral Capacity of Single Vertical Piles Embedded in Choesionless Soil

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ABSTRACT

The paper presents two techniques to improve lateral capacity of single vertical concrete piles embedded in sand. The improvement is achieved by two methods, the first is to use jet grouting to improve soil around the pile to a specific depth and extend. The second way is to enlarge the pile diameter to a certain depth along the top part. The paper illustrates a comparison between the outcomes of two techniques to reveal the most suitable way of improvement. The study is carried out numerically throughout finite element analysis using ABAQUS 6.14 software. The simulated model is verified throughout comparison with published results of both full-scale field tests and numerical analyses. Parametric study through each technique of improvement is conducted to explore the effects of related parameters. The obtained results show that the proposed procedures of improving lateral stiffness of vertical concrete pile reveal considerable effects. Furthermore, the enhancement of ultimate lateral capacity of piles reaches about 160% and the lateral displacement decreased by 35% under the same load. All the obtained results are presented and discussed in a simplified way that can be a guide for future studies and can be used by designer engineers.

Keywords: *laterally, loaded, piles, improvement, grout, enlarged diameter, stiffness.*

1. INTRODUCTION

Pile foundations are often subjected to both axial and lateral loads especially in quay walls, harbor structures, offshore structures, earth-retaining structures, bridges, power stations, lock structures, tall chimneys, and high-rise buildings. The lateral loads are resulted from impact of ships during berthing, soil pressures, wave actions, wind forces, and earthquake effects. The ultimate lateral capacity of vertical piles is limited by soil and pile characteristics.

Over years, many researchers [1, 2, and 3] have developed procedures to predict the ultimate lateral capacity of single vertical piles. They found some difficulties due to non-linear behavior of soil in additional to complexity of interaction between soil and piles. Winkler [1] defined the pile as a beam while the soil was assumed to be independent elastic springs connected to the pile. This model did not take into consideration the effect of nonlinearity of soil. Hetenyi [2] developed further this idea using a linear relationship between lateral deflection of pile and soil resistance. The study deduced fourth order differential equation that related pile deflection with soil resistance. Based on results of field tests, Reese et al. [3] developed p-y relationships, his technique became the most common method used in analysis of laterally loaded piles. This technique assumed the soil as a nonlinear spring connected to an elastic beam which represented the pile. By using the same concept, O'Neill and Murchison [4] developed p-y curves with different forms of equations and coefficients.

Raj and Gandhi [5] investigated the improvement of lateral capacity of single piles embedded in sand by compacting the top layer of soil. The authors carried out experimental models to determine the effects of relative density of the top part of soil, thickness and radius of compacted soil zone. The authors calculated the stiffness factor of single pile (T) and related the thickness and the radius of compacted soil with the stiffness factor value. They concluded that the radius of compacted soil was significant when it became equal to (1.5T), and the thickness of compacted soil was considerable when it reached to value of (T). Lin et al. [6] suggested three methods for improving the performance of laterally loaded pile groups in soft soil. These methods were; i) replacement the top part of soft soil with sand backfill, ii) adding a vertical wall of mixed soil or grout along the side of the pile group, and iii) using a jet grouted zone around and below the pile cap. The authors conducted full-scale tests, their results showed that the enhancement of lateral capacities in the three methods is 20%, 60% and 160% respectively. Sayeed et al. [7] suggested to use vertical sheets of geotextile to improve the ultimate lateral capacity of pile groups embedded in medium sand. They carried out experimental tests in laboratory for several configurations of pile groups with different spacings between piles, location of geotextile sheets, and number of rows. The authors found an increase in lateral loads of pile groups by about 24% in case of using single geotextile layer and about 35% in case of using double geotextile layers.

Abdrabbo, and El Wakil [8] studied the behavior of laterally loaded helical piles in sand. They carried out experimental study in the laboratory by varying helices' diameters, numbers, and spacing. Their outputs illustrated that the presence of helices increases the ultimate lateral capacity of piles depending on the helix's diameter, number, and spacing. Furthermore, they revealed that the improvement ratio reached up to 2.83 at a pile displacement equal to 2.5% of the pile diameter. Stone et al. [9] suggested to use bearing plate on the mud line attached to large diameter monopile embedded in sand to upgrade the lateral stiffness of piles. The authors conducted laboratory tests and numerical parametric study to investigate the performance of the entire system and found significant influence of the bearing plate on the ultimate lateral capacity of the monopiles. They found a decrease in lateral displacement and an increase in the settlement of soil beneath the bearing plate due to the bearing stresses.

The main two factors control the ultimate lateral capacity of piles are; i) characteristics of soil especially soils near the ground surface, and ii) properties of pile material. Therefore, this study aims to improve the upper part of soil in which the pile was installed. The improvement process can be carried out before or after putting the pile into the service. The first case is called preloading improvement, and the later one is called post-loading improvement. The improvement in the first technique is carried out by using jet grout which has advantages of being carried out without any disturbance of piles and superstructure resting on it. While the enhancement in the second technique is carried out by using enlarged diameter in the upper part of the pile to increase its ultimate lateral capacity. The following sections discuss in detail the obtained results.

2. MODEL AND VERIFICATION

2.1 Model

In the present study, numerical simulation of laterally loaded pile is carried out by three-dimensional finite element model using ABAQUS 6.14 software [10]. Soil is modeled using Mohr Coulomb constitutive law which is based on a linear elastic-perfectly plastic behavior while the pile is modeled as a linear elastic material. Meshing is generated automatically by the software taking into consideration some refinement in the soil surrounding the pile to achieve reasonable accuracy of the output results since at pile soil interface strain gradient is relatively high.

The interface between the pile and the soil is defined as surface to surface contact with master and slave nodes implementing friction coefficients. The loads are defined in two steps, the first one is the initial state boundary which is the gravity loads of soil and pile followed by loading of pile. The pile is loaded by imposed specified lateral displacement and hence, the corresponding lateral load is obtained. The applied lateral displacement was gradually increased up to a maximum displacement equal to 10% of the pile diameter.

2.2 Verification of the model

Verification of the three dimensional finite element model used in the current study is done by comparing the obtained results with numerical results of Hazzar et al. [11]. Their outputs are obtained by using FLAC 3D software, which is based on finite difference analysis. Hazzar et al. [11] analyzed a single vertical pile of length 10.0 m and diameter 1.0 m embedded in loose sand. Table 1 demonstrates the properties of soil that considered in their study. Lateral load-displacement relationship of pile head is shown in Fig. 1 along with that obtained by Hazzar et al. [11]. The figure indicates a reasonable conformation between the obtained results with that reported by Hazzar et al. [11].

Table 1: properties of soil of Hazzar et al. [11]

Soil type	Unit weight (kN/m^3)	Elastic modulus (E) (MPa)	Poisson ratio (υ)	Angle of friction (φ) (deg)	Cohesion (C) (kPa)	Friction coefficient
Very loose sand	16	12	0.3	26	0	0.32

Another verification of the used model is conducted by comparing the obtained results with field loading tests that were carried by Comodromos [12]. The field tests were conducted using large diameter piles of 1.0 m diameter, and 52.0 m depth. The soil profile of the site is shown in table 2 and ground water table was found to be at the ground surface. The lateral load-displacement relationships from current study and the measured from field tests are shown in Fig. 2. The figure illustrates that the used model in the current study underestimates the pile head load at displacement equals to 10% of pile diameter by about of 6%. Figures 1 and 2 provide evidence for the considered three-dimensional finite element model to be used for parametric study.

Table 2: properties of soil of Comodromos [12]

Thickness (m)	Soil type	Unit weight (kN/m^3)	Elastic modulus (E) (MPa)	Poisson ratio (υ)	Friction angle (φ) (deg)	Dilation Angle (deg)	Cohesion (C) (kPa)
0-36	Soft clay	20	2.7	0.45	0	0	27
36-48	Medium to stiff clay	20	11	0.45	0	0	110
48-70	Very Dense Sand	22	100	0.3	40	10	0

2.3 P-Y Relationships

The p-y relationships were developed by many researchers such as Reese et al. [3], Greimann et al. [13], and API [14]. However, the p-y relationships are worldwide acceptable and practically in use, these relationships inherent many drawbacks. Notably, the p-y relationships are semi-empirical in nature; the technique was developed based on field tests on small diameter piles. Furthermore, the effects of shear strength between pile and soil were excluded and the effects of pile diameter and pile length were not considered. Therefore, it is interesting to compare these relationships with that obtained from numerical analysis of the current model as shown in Fig. 3.

Different equations suggested by Reese et al. [3], Greimann et al. [13], and API [14] of p-y are used at a depth of 0.25 m below the ground surface to develop p-y relationships. These relationships are compared with the p-y curves obtained by three-dimensional numerical model of the current study as shown in Fig. 3. The comparison reveals huge difference in lateral stiffness and resistance of the pile. The figure points out that the suggested p-y curves underestimate the lateral pile stiffness and lateral resistance which agree with Kallehave et al. [15].

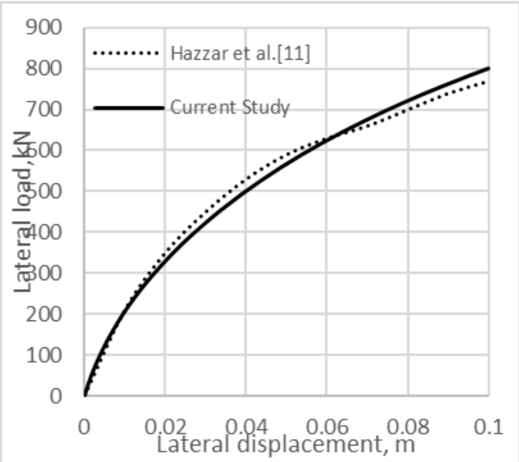


Fig.1: Verification of model with Hazzar et al. [11]

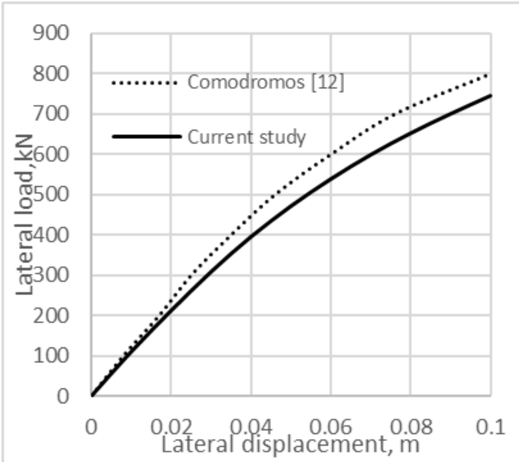


Fig. 2: Verification of model with Comodromos [12]

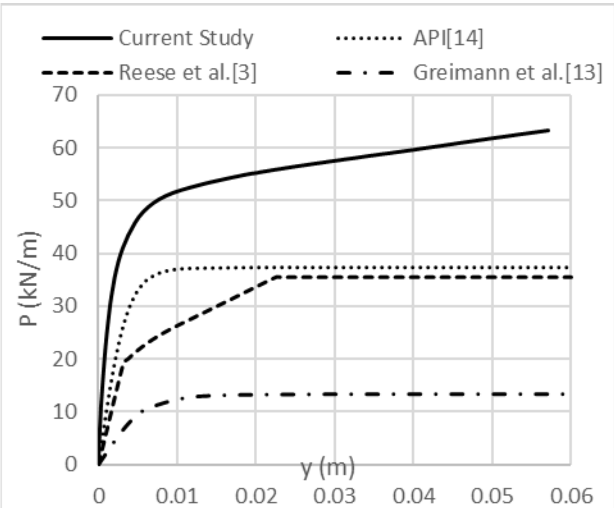


Fig. 3: Comparison between different p-y curves

3. LIMITATIONS OF STUDY

The model has some limitations due to soil constitutive material properties and numerical simulation such as: -

a) The effect of pile installation on soil properties is disregarded.
b) The soil does not exhibit soil hardening.
c) The grouted soil is considered of homogenous state.
d) The bearing sand has homogenous stiffness.

4. STUDIED PARAMETERS

Lateral performance of the pile is affected by pile diameter, pile length and properties of soil surrounding the pile. Therefore, the current study explores the effect of the diameter (D_{im}) and depth (L_{im}) of the improved soil in grouting procedure. In case of pile with enlarged top part, the studied parameters are diameter (D_{up}) and length (L_{up}) of the enlarged section of the pile.

5. JET GROUTING

The jet grouting technique is used in many applications in geotechnical engineering such as enhancing ultimate bearing capacity of shallow foundations and construction of impermeable blug of substructures such as caissons. The application of jet grouting is extended to form grouted columns around the pile to a specific depth to improve the performance of vertical piles subjected to lateral loads. In current study, a single concrete pile of 0.60 m in diameter and 12.00 m in length of slenderness ratio (L/D=20) embedded in dense sand is used. Soil around the pile of diameter (D_{im}), and length (L_{im}) is improved by jet grouted. The properties of pile, sandy soil and grouted soil are shown in table 3 The diameters of the grouted soil (D_{im}) range from 2 to 5 times the pile diameter and the lengths of the grouted soil (L_{im}) vary between 10% and 50% of the pile length. The friction coefficient between pile and soil (μ) is calculated from Randolph and Wroth [16] equation as following: -

$$\delta = tan^{-1}\left(\frac{cos(\varphi)*sin(\varphi)}{1+sin^2(\varphi)}\right) \quad (1)$$

$$\mu = \tan(\delta) \quad (2)$$

In which

(φ) is the critical state angle of soil.

(δ) is the friction angle between soil and pile.

Table 3: Material properties used in current study

Material type	Constitutive law	Unit weight (kN/m^3)	Elastic modulus (E) (MPa)	Poisson ratio (ν)	Friction angle (deg)	Dilation angle (deg)	Cohesion (C) (kPa)
Dense sand	Mohr Coulomb	20	50	0.3	35	5	0
Grouted soil	Mohr Coulomb	22	100	0.3	38	8	50
pile	Elastic	25	25000	0.2	--	--	--

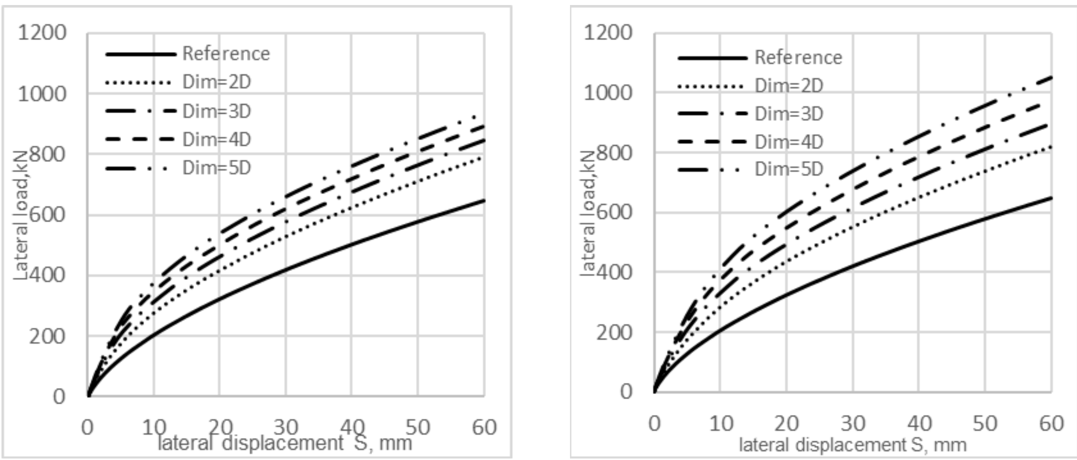
The pile is loaded with stepwise lateral displacement up to a displacement of pile head equal to 10% of pile diameter. Load-displacement relationships are shown Fig. 4 which shows that an increase of lateral pile capacity is gained as the improved soil diameter increases. Also, the pile capacity of lateral loads is dependent on the length of improved soil around the pile. To detect the increase in the lateral loads, a factor is defined as load improvement factor (I_p), which is the ratio of ultimate lateral load after improvement divided by the ultimate lateral load before improvement at the same displacement. The increase in ultimate load is associated with an increase in lateral stiffness of the pile. The improvement process decreases the lateral displacement of pile head compared to displacement of the pile head before improvement at same loads. Another ratio is introduced for displacement (I_d) which is defined as the ratio between pile head displacement after improvement and pile head displacement before improvement at the same pile load.

The load improvement factors (I_p) at different ratios of improved length (L_{im}/L, %), are obtained and drawn versus (S/D) in Fig. 5. The load improvement factors start to increase slightly in the beginning of pile movement and tend after that to decrease to reach its final value but never drop below 1.18 in any of the studied cases. This decrease during the pile movement may be attributed to that the stresses in the improved soil reach its plastic state later than in the original soil. Furthermore, the improved soils may exhibit strain softening.

The values of load improvement factor at (S/D = 2%), and (S/D = 10%) are presented versus ratios of improved lengths in Fig. 6. The figure indicates that (I_p) increases up to a peak value corresponding to (L_{im}/L) equal to 20%, then it descends to attain a final stabilized value, but never drops lower than 1.18 in any of studied cases. This can be attributed to that any improvement of soil below the effective length of the pile (L_{eff}) does not affect the pile performance under lateral loads.

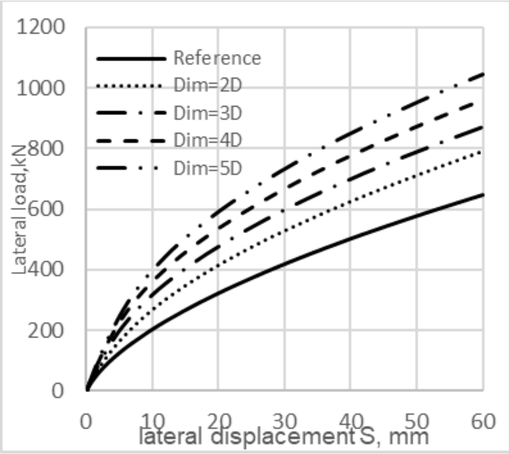
The displacement improvement ratios (I_d) are calculated and drawn ratios of improved lengths in Fig. 7 which clarify that (I_d) descends with the increase of improvement length ratio until its lowest value at 20% improvement length of the pile, then it attains final stabilized value.

Initial and secant lateral stiffnesses of pile in improved soil are calculated and found to be upgraded due to soil improvement which is detected by a new factor called as stiffness improvement factor (I_s) that is defined by the ratio of initial or secant stiffness of soil after improvement and the corresponding stiffness of soil before improvement. The stiffness improvement factors are calculated for initial and secant stiffnesses and drawn in Fig. 8. The stiffness improvement factors showed in Fig. 8 increase until its peak value at 20% of improvement length of pile, then they descend to attain a final stabilized value, but never drop lower than 1.22 in any of the studied cases.

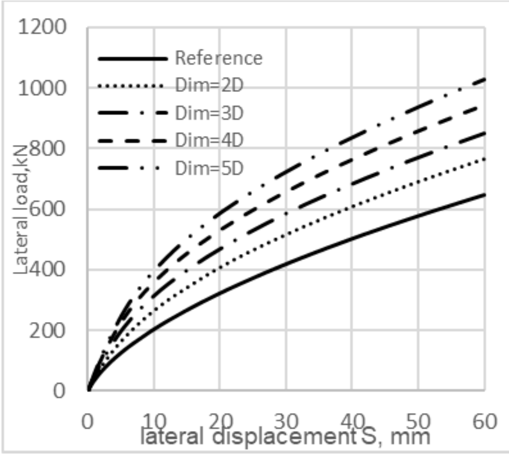


a) L_{im}/L =10% b) L_{im}/L =20%

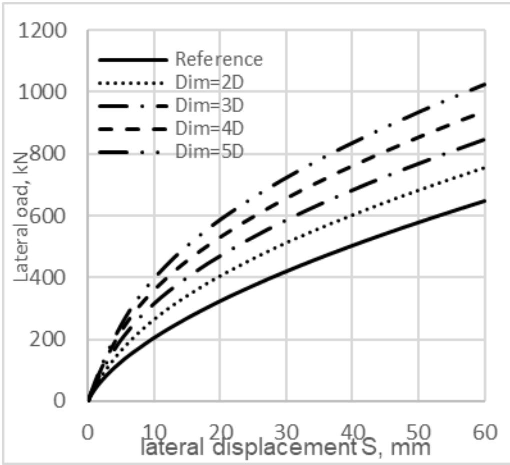
Fig. 4: Load-displacement relationships of pile in improved soil by jet grouting



c) L_{im}/L =30%

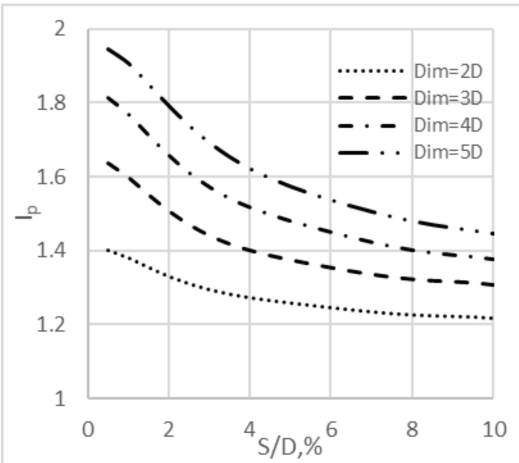


d) L_{im}/L =40%

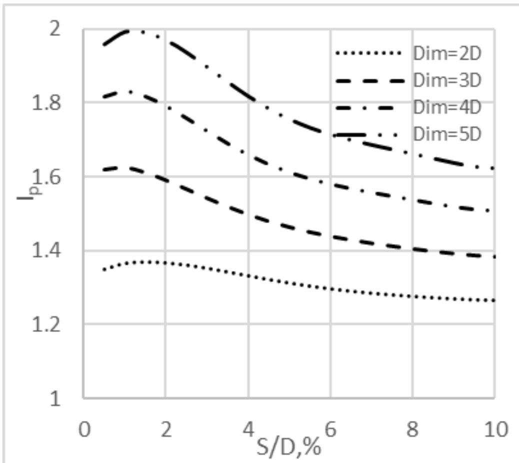


L_{im}/L =50%

Fig. 4 cont.: Load-displacement relationships of pile in improved soil by jet grouting

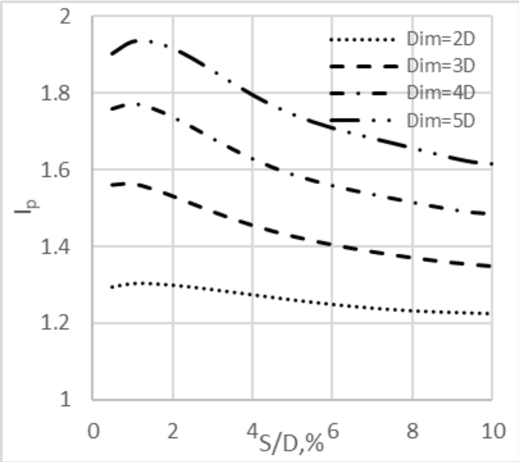


a) L_{im}/L= 10%

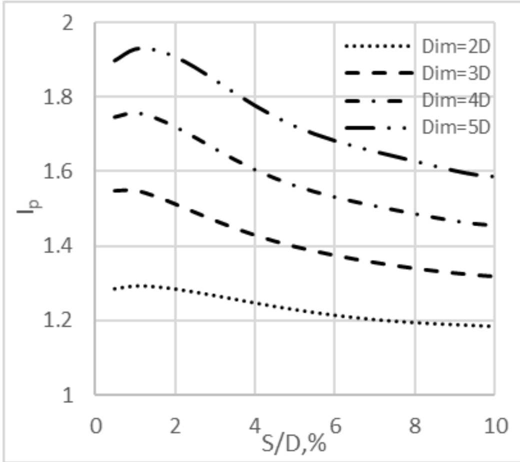


b) L_{im}/L= 20%

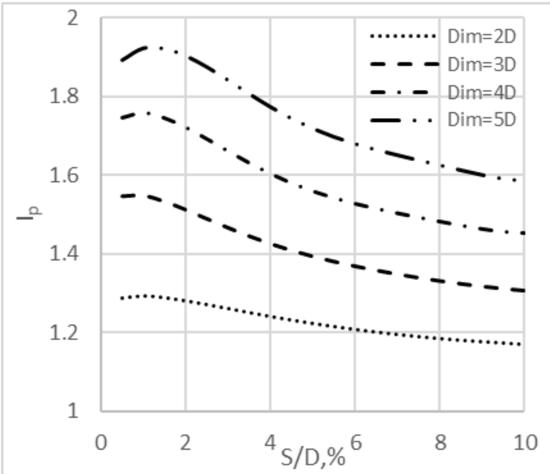
Fig. 5: load improvement factors versus S/D, jet grouting



c) L_{im}/L= 30%

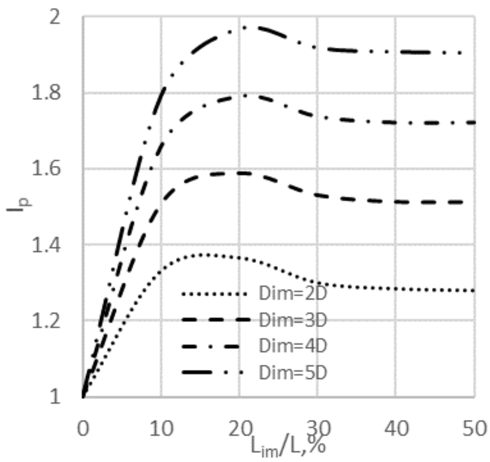


d) L_{im}/L= 40%

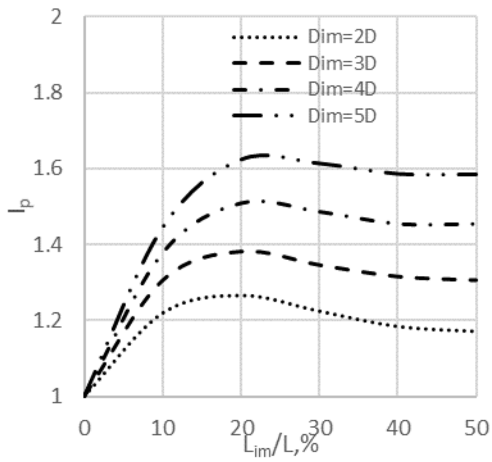


e) L_{im}/L= 50%

Fig. 5: cont. load improvement factors versus S/D, jet grouting



a) S/D=2%



b) S/D=10%

Fig. 6: Load improvement factors versus improved length of jet grouting.

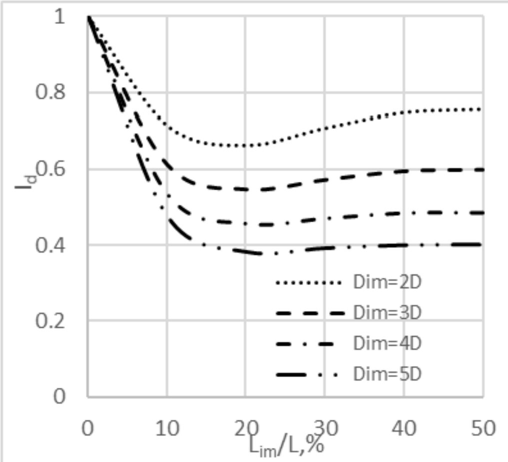
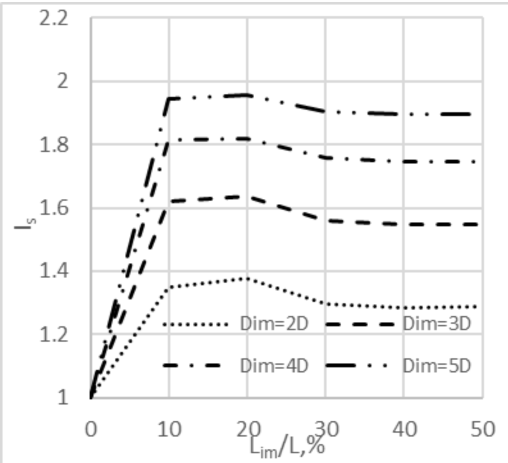
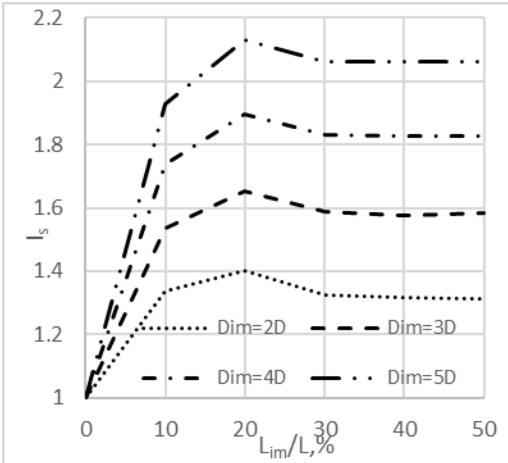


Fig. 7: Displacement improvement ratios versus improved length of jet grouting.



a) Initial Stiffness



b) Secant Stiffness

Fig. 8: Stiffness improvement factors versus improved length of jet grouting.

6. ENLARGED DIAMETER PILE

This technique of enhancing pile performance against lateral loads can be carried out during execution of the pile. The top part of the pile can be formed with a diameter bigger than that the lower part. The pile has two sections, the first section is the upper part of the pile and is called upper section in which the pile diameter is enlarged to a certain depth. The second section is the rest of the pile and is called lower section. The pile shall be dissimilar with respect to diameter so, it is advisable to study the behavior of piles in a group taking into consideration dissimilar piles.

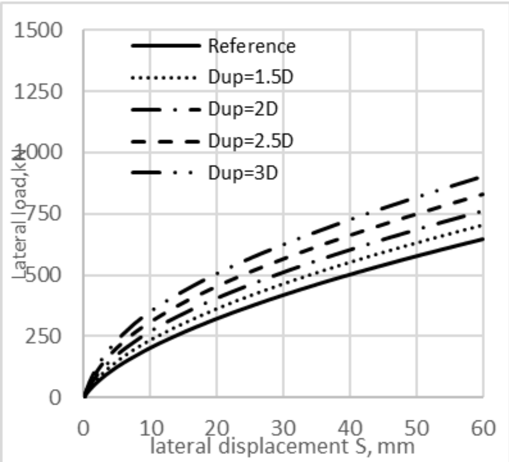
The diameter of upper section is denoted (D_{up}) and the length of it is denoted (L_{up}). A parametric study is carried out by varying the diameter (D_{up}) of the upper section from 1.5 to 3.0 times the diameter of the lower section (D). The length of upper section (L_{up}) also is varying between 8.3% and 25% of pile length.

The load-displacement relationships for different (D_{up}) and (L_{up}) are presented in Fig. 9. This figure indicates that an increase of lateral load capacity is accompanied with an increase of improved diameter and length. The figure shows that the lateral load is directly proportion with (D_{up}) and (L_{up}). The variation of (I_p) with (S/D) is presented in Fig. 10, while the stabilized improvement factors of various diameter at (S/D = 2%) and (S/D = 10%) are plotted in Fig. 11, which shows an increasing of the values of (I_p) with length and diameter of upper section.

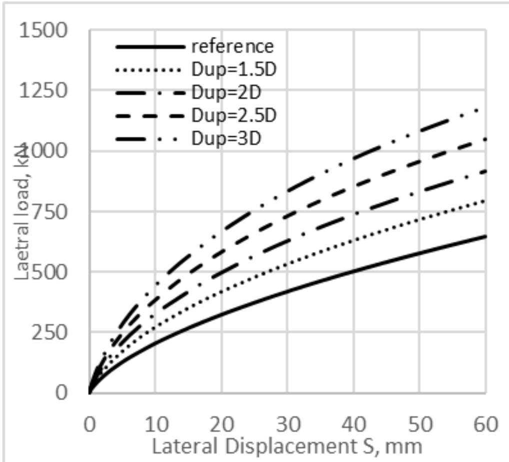
The enlargement of pile diameter has significant effect on lateral displacement of pile head as shown in Fig. 12. The displacement improvement ratios (I_d) tend to decrease to reach its lowest value at the final value unlike grouting.

Initial and secant lateral stiffness improvement factors (I_s) of various enlarged pile diameters are calculated and drawn in Fig. 13 which are found to be upgraded due to improvement. Unlike grouting, the initial and secant stiffness improvement factors (I_s) increases without any decrease.

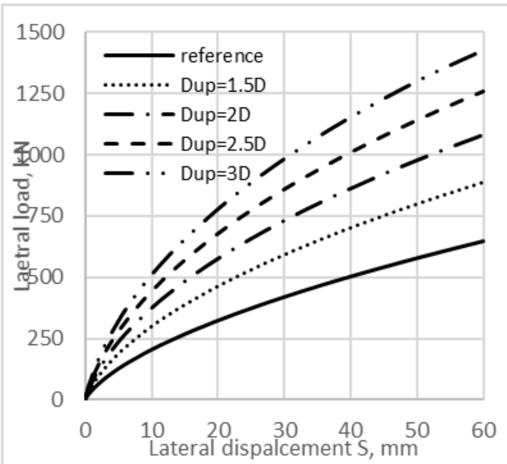
The enlargement of pile diameter has more effect on (I_p), (I_d), and (I_s) than the grouting procedures due to the higher strength of concrete material than grouted soil and due to fully bonded connection of improved upper zone of pile to the original piles section while the grouted soil has the ability to slide along the original pile which leads to a relatively weaker overall stiffness of the system.



a) L_{up}/L= 8.3 %

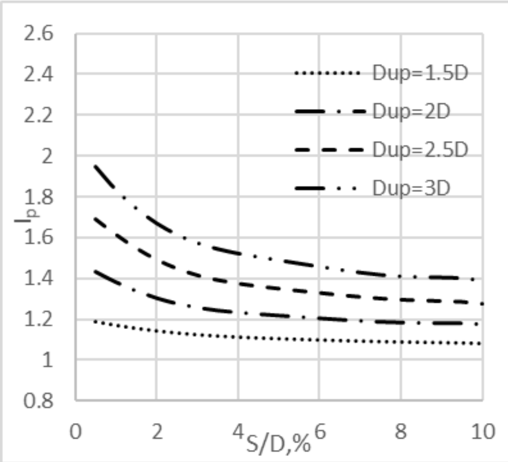


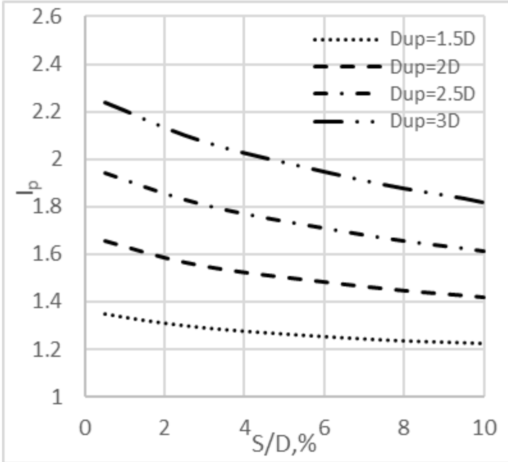
b) L_{up}/L= 16.6%



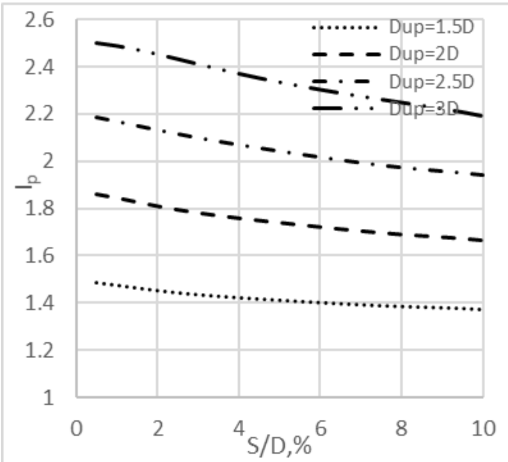
c) L_{up}/L= 25%

Fig. 9: Load-displacement relationships of enlarged pile diameters.



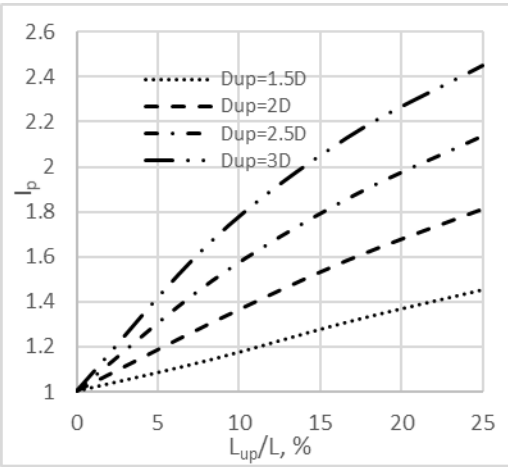


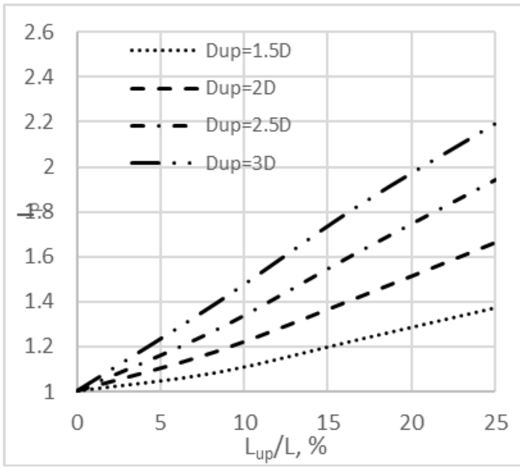
a) L_{up}/L= 8.3%   b) L_{up}/L= 16.6%



c) L_{up}/L= 25%

Fig. 10: Load improvement factors versus (S/D).





a) S/D=2 %   b) S/D=10 %

Fig. 11: Load improvement factors versus enlarged section length.

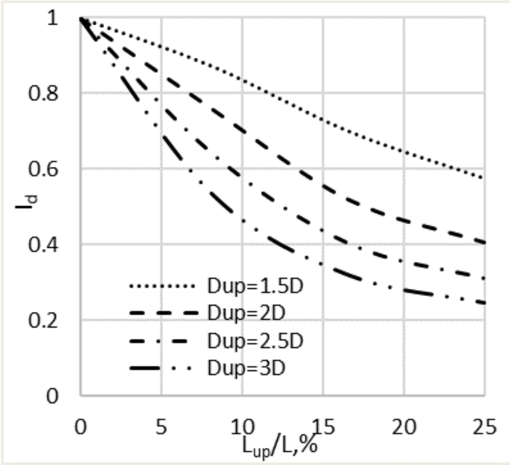


Fig. 12: Displacement improvement ratios versus enlarged section length.

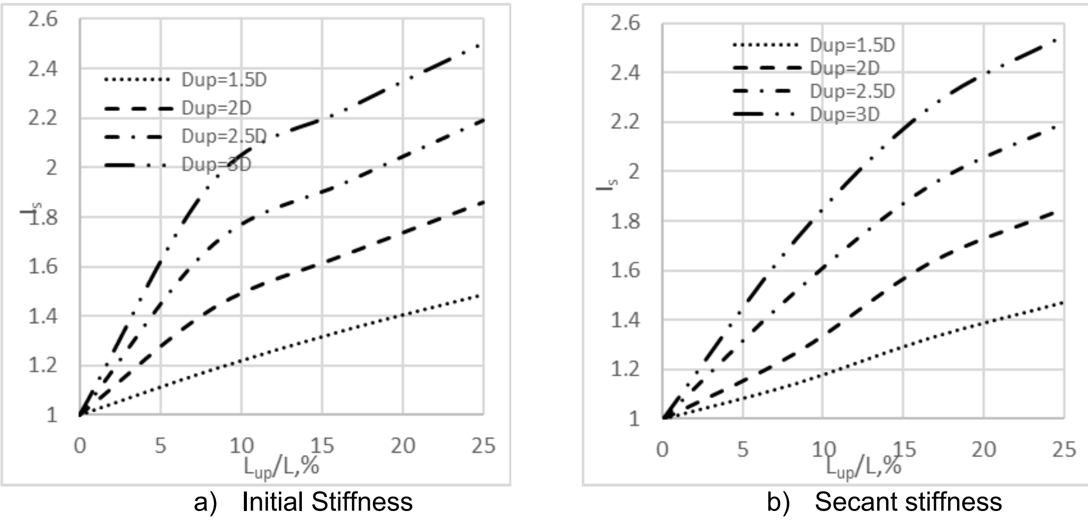


Fig. 13: Stiffness improvement factors versus enlarged section length.

7. CONCLUSIONS

Improvement of the lateral performance of vertical piles has a great importance, so existing pile can be reused for bigger superimposed lateral loads. Furthermore, vertical piles can be attentionally improved to sustain higher lateral loads. The present research is focusing on improvement of the lateral performance of vertical concrete piles. From the numerical analysis of three-dimensional finite element model, the following conclusions are revealed: -

1) Significant increase in the ultimate lateral capacity of piles using jet grouting and enlarged pile diameter can be achieved.
2) The load and stiffness improvement factors are directly proportion with the diameter of improved soil by jet grouting and enlarged pile diameter. The improved length of jet grouting has different effect on load and stiffness improvement factors. The improvement factors increase up to it is a peak value at about 20% of the pile length and after that they tend to decrease to maintain stabilized values.
3) The displacement improvement ratios in jet grouting are lessening until they reach their minimum value at improved length of 20% from the pile length and after that are stabilized, while in enlarged pile diameter, they are lessening without any minimum value.
4) The enlarged pile diameter procedure has more effect on load improvement factor (I_p) than the jet grouting improvement at same diameter and length of improvement. Also, the displacement of enlarged pile diameter is less than of jet grouting.

5) The enlarged pile diameter procedure is more effective on initial and secant stiffness than jet grouting procedure.

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