Comparison of Single and Group Jet Grout Columns Settlement Based on Field Test and Theoretical Methods

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Abstract. The settlement evaluation for the jet grouted columns (JGC) in soft soils is a problematic matter, because it is influenced by the number of aspects such as soil type, effect mixture between soil and grouting materials, nozzle energy, jet grouting, water flow rate, rotation and lifting speed. Most methods of design the jet-grouting column based on experience. In this study, a prototype single and group jet grouting models (single, 1×2, and 2×2) with the total length and diameter were (2000 and 150 mm) respectively and clear spacing (3D) has been constructed in soft clay and subjected to vertical axial loads. Furthermore, different theoretical methods have been used for the estimation of (JGC) settlement. Pile load settlement analysis of the jet grout columns showed that the average settlement values were (0.41, 0.663, and 1.5 mm) for the single, group (1×2) and group (2×2) jet grouted columns respectively. While, in the theoretical methods give a higher value of the settlement (2.0, 3.48, and 5.24 mm) for the single, group (1×2) and group (2×2) jet grouted columns compared with the settlement results acquired from field pile load test data. Therefore, it is not recommended to be used for soft clay. On the other hand, Fuller and Hoy’s, Hansen’s 90%, and Butler and Hoy’s results may be considered faithful interpretation methods for the single and group (1×2 and 2×2) (JGC).

Keywords: Settlement, jet grouted columns, theoretical analysis. Pile load test.

1. Introduction
The construction activities in the south of Iraq often request deep foundations for the reason of the insignificant engineering properties of the subsoil and the associated difficulties arising from weak soil at surface depths. The structures erected on such soils may suffer from over settlement. Consequently, the soil improvement by Jet Grouting is one of the suitable techniques in improving the weak soil. The major purpose of grouting is to fulfill the space of the formatting material by replacing the current fluids with the grout and in that way improving the engineering properties of the soil, in this technique, the cement slurry is injected into the ground and column of hardened soil is obtained with required diameter and depth. Therefore, the strength of soft soil is increased when using this method, and the load is transferred from the foundation to both the jet grout columns and the original soils [1]. Jet grouting is a soil treatment technique adoption of a high hydraulic energy to destroy the surrounding soil. Ground improvement by Jet grouting technology can be used in varied and difficult geological and geotechnical situations, showing its practical and economic advantages, in addition to the importance of the performance control on-site, before and during the construction of the final foundations [2].

The Jet grouting has increased uses in the last years in the ground improvement that effort of low strength, permeability and seepage problems. The jet grouting has a high potential application to decrease the settlement in embankments [3]. Jet grouting technology has become popular because of installation it’s very easy of, low cost, low noise, and no vibration accrues. So, it’s best suitable,
especially for the city constructions, noise, vibration, and site limitation area is limited [4,5]. Bustamante [7] conducted the back analysis of a large number of results from axial load tests performed on jet grouting soil-cement columns prepared with removable extensometers [6].

According to the interaction between the jet grout column installations of soil-cement reinforcing elements significantly increase the serviceability of the foundation utilizing increasing its strain characteristics and active protection of soils from the influence of the seismic vibrations, providing for the safe operation of the sports structure [7]. Juzwa and Bzówka [8] showed that the highest settlements of jet grouting columns from the center of the group and if the group is larger (more columns in the group) than the values of settlements are increasing [8].

The jet grouting method is one of the greatest common techniques for strengthening soft soils. Jet grouting columns allow for transmitting substantial loads through the reinforced soft soils and reduce the construction's settlement [9,10]. Different techniques have been used to prepare the (JGC) and measure their properties, but those methods are site-reliant, and involve numerous limitations in terms of jet grouting techniques, soil types, and jet grouting effective parameters. So that, the greatest way to estimate jet grouting execution and soilcrete properties is by conducting a prototype model to simulate the jet grouting or pile foundation in a field by the real soil state and with real jet grouting parameters and apparatus. The real jet grouting equipment is very large to be used. A choice was made for this mission to design and construct machines of jet grouting apparatus that would have almost a similar capability as a real field apparatus but with less size and cost.

2. Field Investigation and Soil Sampling
The site of the conducted study was located at the distance (100) m from the Euphrates River, in Al-Nasiriyah city (375) km southeast of Baghdad as shown in Fig. 1. The site investigation included drilling borehole 10 m in length and the basic physical and mechanical properties of the soil are represents in Tables 1 to 5.

![Figure 1. Location of the study area.](image)

### Table 1. Results for corrected SPT at the specified depth.

| Depth (m) | SPT | $q_u$ (kPa) based on Terzaghi and Peck, (1967) [19] |
|-----------|-----|--------------------------------------------------|
| 1.0-1.5   | 5   | 60                                               |
| 5.5-6.0   | 7   | 87                                               |
| 7.5-8.0   | 8   | 100                                              |

### Table 2. Results of undrained shear strength and consistency.

| Depth (m) | $q_{unconfined}$ (kPa) | $c_u$ (kPa) | Consistency based on Terzaghi and Peck, (1967)[19] |
|-----------|------------------------|-------------|---------------------------------------------------|
| 1.5-2.0   | 73                     | 36          | Soft                                              |
| 2.5-3.0   | 42                     | 21          | Very soft                                         |
| 3.5-4.0   | 76                     | 38          | Soft                                              |
| 4.5-5.0   | 86                     | 43          | Medium                                            |
Table 3. Soil Properties.

| Depth (m) | Sample type | LL % | PL % | PI % | Gs  | Water content % |
|-----------|-------------|------|------|------|-----|-----------------|
| 0.0-1.0   | DS          | 32   | 15   | 17   | 2.61| 34.73           |
| 1.5-2.0   | US          | 34   | 19   | 15   | 2.62| 35.26           |
| 2.5-3.0   | US          | 60   | 29   | 31   | 2.78| 37.95           |
| 3.5-4.0   | US          | 59   | 30   | 29   | 2.76| 38.22           |
| 4.5-5.0   | US          | 35   | 21   | 14   | 2.58| 33.71           |
| 8.0-10.0  | DS          | 36   | 21   | 15   | 2.61| 34.78           |

Table 4. Summary of consolidation test results.

| Depth (m) | $P_c$ (kPa) | $C_c$ | $C_r$ | $C_v$ (mm$^2$/sec) | $e_o$ | $e_f$ |
|-----------|-------------|-------|-------|---------------------|-------|-------|
| 0.0-2.0   | 70          | 0.529 | 0.0598| 0.02               | 0.63  | 0.475 |

Table 5. Soil description and classification.

| Depth (m) | Groundwater table (m) | $\gamma_{we}$ (kN/m$^3$) | Clay (%) | Silt (%) | USCS |
|-----------|------------------------|---------------------------|----------|----------|------|
| 0.0-1.0   | 0.75                   | ****                      | ****     | ****     | Fill |
| 2.0-2.5   |                        | 20.48                     | 61       | 39       | CL   |
| 2.5-3.0   |                        | 21.02                     | 70       | 30       | CH   |
| 3.5-4.0   |                        | 21.98                     | 72       | 28       | CH   |
| 4.5-7.5   |                        | 21.5                      | 60       | 40       | CL   |
| 7.5-8.0   |                        | 21.4                      | 62       | 38       | CL   |

3. Jet Grouting Field Design
To implement the jet grouting technique, it is necessary to design and manufacture an actual jet grouting system to simulate the actual process to great soilcrete column. The main equipment of the system includes, as shown in Fig.2 and Table 6.

Figure 2. Jet grout machine and parts.
Table 6. The main equipment and parts of the jet grouting system.

| Jet Grouting Technique     | Important performance                                                                 |
|---------------------------|----------------------------------------------------------------------------------------|
| Jetting Grouting Machine  | The water pump rate is (11 L/min) with maximum pressure (200 bar) at a maximum speed of 1600 rpm |
| High-pressure water pump  | a progressive cavity pump with rated capacity (5.0 m3/hr.), a rated differential pressure (3.0 bar), rated speed (1450 rpm) and maximum allowable casing pressure (10 bar) |
| High-Pressure Grouting Pump| The cylindrical mixer is made from an iron with 800 (mm)-in height and 500 (mm) in diameter. |
| Mixer Unit                | Electroformed Nickel and Brass nozzles with the diameter 2(mm), and 3 (mm).            |
| Nozzle                    |                                                                                       |

4. Material and Methods
The construction theory of jet grouting was double fluid system (water, grout, and zero air pressure to reduce the diameter of the column) can be represented as:

- The water jet was at first used to create borehole to the required depth under pressure 75 bar. The drilling tools generally rotated at a continuous rate of 30 rpm to erode the soil and create column geometry.
- After the erosion process has done, the high pressure of grout slurry (Portland cement and water) was 6 (bar) with water-cement ratio (1:1) injected into the hole. In general, the setting time of the hardening slurry and soil mixture was 24 hr. On the other hand, the total time of the process to complete the drill the borehole by water jetting and slurry injection to build up the soilcrete was 2 hr. As a result, the shape of the soilcrete column was regular and looked as the cylinder and the cross-sectional diameter of the column was measured at the top (0.5-0.6 m) from the column head. All construction works of the group are represented in Fig. 3.

Figure 3. Construction steps of single, group (1*2), and (2*2) jet grout soil-cement column (D=150 mm and L=2000 mm).

4.1 Construction of Concrete Cap for Jet Grouted Column
A reinforced concrete cap was required for transferring the loading forces from the assembly (Structure of kentledge blocks) to the soil-cement column during the pile load test. Figure 4 depicts the schematic of the reinforcement concrete cap head connection. The dimensions of cap and steel reinforcement for concrete cap was calculated according to meet standard code requirements (ACI 318-14) [11]. The formwork fabricated for casting the concrete cap is displayed in Fig. 5.
4.2. Pile Load Test
The two important features considered in the design of jet grout soil-cement columns are the bearing capacity and expected settlements due to affected axial loads. The jet grout capacity can be estimated using a theoretical method based on Poulos and Davis (1980) [12]. Usually, these methods tend to calculate approximately the jet grout column capacities with variable degrees of accuracy. The best accurate method to evaluation of the jet capacity and settlements are to make full-scale load tests representing the real column behavior normally expressed in terms of a load-settlement relationship. Although, the shortcomings of this method contain the relatively long time required and high budgets undertake in performing such tests. Furthermore, it would not be feasible to perform pile load tests in the stage of the project planning stage. They are frequently controlled during the construction phase on construction piles which cannot be loaded to failure [13].

4.2.1. Quick Pile Load Test. The Quick pile load test procedure presented in (ASTM-D1143, 2007) [13]. Use the test load for an increment of 5% of the expected failure load. Add load increments until accomplishing a failure load but do not exceed the safe structural capability of the pile, pile group, or loading apparatus. Through each load interval, save the load continual for a time interval of not more than 4 min and not more than 15 min, by the same periods for all loading increments during the test (ASTM-D1143, 2007).

4.2.2. Evaluation of the Jet Grout Load-Settlement Results-Based to Interpretation Methods. To compare the total settlement results of the pile load test for jet grouting soil-cement column four designated interpretation methods were chosen to inspect their accuracy for the calculated total settlement. In general, no exact method or criteria that can clearly describe the exact ultimate load or total settlement. However, these methods including settlement requirements mathematical and graphical methods [14,15].
• Brinch Hansen’s 90% Method (1963).
• Butler and Hoy’s Method (1977).
• Fuller and Hoy’s Method (1970).

4.2.3. Single and Group Jet Grout Column Settlement. Most deep foundations requirements for the designing method will have the total accepted settlements of no more than about 12 mm. The total settlement estimations of a single and group jet grout column settlement are it’s treated as the pile and consisting of the elastic settlement of a single pile and consolidation settlement below the pile group. Furthermore, the elastic settlement of single pile always related to many factors, such as; the relative
stiffness of the pile material and the surrounding soil ($K_{ps} = EP/ES$), the ratio between length to diameter ratio ($L/D$). On the other words, the relative stiffness of the base ($E_{sb}$) and over the pile length and the modulus of elasticity of the soil and distribution ranges along the depth of the pile. Therefore, various methods have proposed to analyze and calculate the total settlement for the single pile and pile group as described by:

Method 1: Described by Budhu [16]:

Poulos (1989) as cited by [16] explained an excellent discussion to calculate settlement based on various numerical procedures, the total settlement of a single pile consists of settlement based on skin friction as explained in Eq. (1):

$$\rho_{ES} = \frac{Q_{all,friction}}{E_s L} I$$

$I = 0.5 + \log\left(\frac{L}{D}\right)$

Poulos, (1989) developed estimation for elastic settlement for floating pile as explained in Eq. (2):

$$\rho_{ES} = \frac{Q_{all,friction}}{E_s D} I_p$$

$I_p$: influence factor depends on the $L/D$ and $K_{ps}$ [16].

Settlement based on end bearing assuming the pile base is a rigid and punches on the surface of the soil transferred at a depth. The base settlement based on Timoshenko, and Groodier [16] is explained in Eq. (3):

$$\rho_b = \frac{Q_{base r_b G_b}}{1 - \nu^4}$$

Where; $\nu$, Poisson’s ratio of soil, $r_b$ and $G_b$ are the radius and shear modulus at base. The elastic shortening of a single pile is presented in Eq. (4):

$$\rho_p = C \frac{Q_{all,friction}}{E_p A_p}$$

Where $C$ is the reduction factor ($C \approx 0.5$ for most soil, and $C \approx 0.7$ for soft soil). The shortening settlement calculates only when ($E_P/E_S < 500$). The total elastic settlement can be shown in Eq. (5):

$$\rho_{ET} = \rho_{ES} + \rho_b + \rho_p$$

Pile group settlement calculations based on settlement of single pile through a group the settlement factor $Rs$, as;

$$Rs = \frac{\text{settlement of group}}{\text{settlement of single pile at same average load}}$$

Fleming, et al. [16] gives an empirical solution of $Rs$: $Rs = n^\varphi$ where $\varphi = 0.4 - 0.6$ and $n =$ number of the pile in the group. The consolidation settlement under the pile group based on the pile group may be embedded in soft soil and transfer the load causes consolidation settlement, the full load design act at depth $2/3L$ and the distribution according to the 2:1.

Method 2: Described by Das [17] explained that the total settlement of single pile caused by a vertical working load is:

$$S_{ET} = S_{E1} + S_{E2} + S_{E3}$$

Where $S_{E1}$ is the elastic settlement of the pile, $S_{E2}$ is settlement caused by the vertical load at the pile tip, and $S_{E3}$ is settlement caused by the transmitted load along the pile shaft. The total settlement can be represented in Eqs. (6, 7, and 8):

$$S_{E1} = \frac{(Q_{WR} + Q_{WS}) L}{A_P E_P}$$
\[ S_{E2} = \frac{(Q_{WP}D)(1-\mu^2)I_{WP}}{E_s} \] (7)

\[ S_{E3} = \frac{(Q_{WS}D)(1-\mu^2)I_{WS}}{P.L.E_s} \] (8)

Vesic (1977) explained another semi-empirical solution to obtaining the magnitude of the settlement as in Eq. (9 and 10) [17].

\[ S_{E2} = \frac{Q_{WP}.C_P}{D.q_p} \] (9)

\[ S_{E3} = \frac{Q_{WS}.C_S}{L.q_p} \] (10)

Where \( Q_{wp} \) is the load carried at the pile point, \( Q_{ws} \) is the load carried by frictional (skin) resistance, \( A_p \): area of a cross section of pile, \( L \) is the length of pile, \( E_p \): modulus of elasticity of the pile material, \( \xi \) is the amount of varies between 0.5 and 0.67 and will depend on the nature of the distribution of the unit friction resistance along the pile shaft, \( D \) is the diameter of pile, \( Q_{wp} \) is the point load per unit area at the pile = \( Q_{wp}/A_p \), \( E_s \) is the modulus of elasticity of soil at or below the pile point, \( \mu \), is Poisson’s ratio of soil, \( I_{wp} \) is the influence factor = 0.85, \( q_p \) is the point resistance of the pile, \( C_p \) is the empirical coefficient. Representative values for various soils are given below, \( P \): perimeter of the pile, \( L \) is the length of pile, \( I_{ws} \) is the influence factor = \( 2+0.35(L/D)\)\(^{0.5} \), \( C_s \) is an empirical constant = \( (0.93+0.16(L/D)\)\(^{0.5} \). \( C_p \): values (0.03-0.06) for bored pile. In general, a group pile elastic settlement at a similar working load on each pile increases with the width of the group (Bg) and the center-to-center spacing of the piles (d). The simplest relation for the settlement of group piles was given by Vesic, Eq. (11) [16]:

\[ S_e (G) = \left( \frac{B_g}{d} \right)^{0.5} S_e (single \ pile) \] (11)

Bg: width of pile group.

The consolidation settlement of a group jet grout column in clay can be estimated by using the 2:1 stress distribution method. The elastic jet grout column settlement, \( E_j \), is determined according to the uniaxial compression strength (UCS). After completing the pile load test process, a series of core barrel samples were taken from different depths of jet grouting columns using the continued Coring method. The uniaxial compressive strength (\( F_c = 4.57 \)MPa), \( E_j:=175*q_{u(jet)}= 175*4.57=800 \) MPa, the modulus of soil is equals (\( E_s=9000 \)), Poisson ratio for soft clay soil, \( \nu =0.5 \) [18].

5. Determination of Jet Column Load – Settlement Capacity

In performing a pile load test, two settlement dial gauges were used to record the average vertical settlement of the jet grouting columns. The dial gauges were fixed to the reference beam. The arrangement of the load reaction was consist of a platform consist of iron H-beam section, the end of platform rested over timber grabbing and then overreaction support, the applied load on the head of pile consist of the load of the platform and dead load of heavy material (a kentledge) were supplied by using a concrete blocks Fig.6.
The subsequent results supported the observation of full-scale models of in situ check results of the jet grouting soil-cement column. Several limits influenced the depth and diameter of jet grout soil-cement columns like jetting pressure, radial rotation, and vertical motion of rod, the operation values and results will be listed in Table 7 and illustrated in Fig 7. Many interpretation theories have been proposed for estimation ultimate axial bearing capacity of jet grouted soil columns. A comparison was made between the measured settlement of single and group jet grouting soil-cement column were listed in Table 8. According to the load settlement test results of the jet grouted column, the total head settlement and for single and group were increases with increasing numbers of jet grout columns in a group as shown in Fig. 8.

**Table 7.** Operational parameters and dimensions were used in constructing the jet grouting soil-cement columns (D=150 mm).

| Category of JGC      | Pile Dimensions | Pile Cap Dimension | Water Jetting Pressure (bar) | Grouting Jetting Pressure (bar) | Rode Rotation Motion (rpm) | Rod Vertical Motion cm/min |
|----------------------|-----------------|--------------------|------------------------------|---------------------------------|----------------------------|--------------------------|
| Single               | 150             | 2000               | D=150                        | 75                              | 6                          | 40                       | 40                       |
| Group (2*1)          | 150             | 2000               | (500*960)                    | 75                              | 6                          | 40                       | 30                       |
| Group (2*2)          | 150             | 2000               | (960*960)                    | 75                              | 6                          | 40                       | 30                       |

**Table 8.** Summary of theoretical and measured settlement of jet grouting column (D=150 mm).

| Jet grout references | Category of Measured Settlement (mm) | Category of Theoretical Settlement (mm) |
|---------------------|-------------------------------------|----------------------------------------|
|                     | Hansen’s 90% Method | Butler and Hoy’s | Fuller and Hoy’s | Average | Poulos | Vesic’s | Average |
| Single              | 0.45                  | 0.47                        | 0.32                        | 0.41                | 1.625               | 2.41                  | 2.0178               |
| Group (2*1)         | 0.62                  | 0.73                        | 0.64                        | 0.663               | 3.423               | 3.533                 | 3.48                 |
| Group (2*2)         | 1.5                   | 1.65                        | 1.35                        | 1.5                 | 4.08                | 6.4                   | 5.24                 |
Figure 7. Load settlement curves of single and groups of jet grout soil-cement columns (D=150 mm and L=2000 mm and S/D=3).

Figure 8. Comparison of Field and Theoretical Settlement.

Comparison of Interpreted and Measured Settlement. To comparison of interpreted total settlement and measured settlement based on Poulos and Das, the ratio of interpreted total to measured settlement (ST/Sm), expressed in percent were illustrated in histograms from Fig. 9 and Fig. 10 for single and group jet grout soil-cement column. The line 100% of Poulos and Vesic’s represents a basis for comparison, the value of (ST/Sm) higher than 100% indicate to overestimation, whereas, lower than 100% indicate an underestimation of the total settlement, from the figures, it may be noted that:

- The settlement of a single and group jet grout soil-cement column estimation by Hansen’s 90%, Fuller, and Hoy’s and Butler and Hoy’s Method given underestimation value to measure value by Poulos about (18.11 to 40.44%).
- The settlement of a single and group jet grout soil-cement column estimation by Hansen’s 90%, Fuller, and Hoy’s and Butler and Hoy’s Method given underestimation value to measure value by Poulos about (13.28 to 25.78%).
6. Conclusion
The analysis of deep foundation settlement was performed employing the most widely used standards and approaches. To compare the results of the pile load test for jet grout soil-cement column settlement, three selected interpretation methods such as Hansen’s 90%, Butler and Hoy’s, and Fuller and Hoy’s were chosen to examine their accuracy for calculating settlement. According to the pile load test analysis, it has been exposed that the jet grout soil-cement column settlement increase with an increase in the number of jet grout column. The comparative analysis results of methods indicate that the settlement values are similar for interpreted methods for the single and the group jet grout column while, the largest value of jet grout column settlement was obtained based on the Das methods. The reliable results of pile settlements were obtained from Fuller and Hoy’s, and Hansen’s 90% method. At last, the best way for computation and prediction of jet grout column settlement in soft clayey soils is a pile load test and use the average value of the settlement from the adequate interpretation methods.

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