Field study of the effect of jet grouting parameters on strength based on tensile and unconfined compressive strength

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Abstract. The improvement of the mechanical soil characteristics of jet grouting technique is very attractive. The jet grouted soil cement columns in soft is a complicated issue because it depends on a number of factors such as, soil nature, mixture, influence among soil and grouting materials, jetting force of nozzle, jet grouting and water flow rate, rotation and lifting speed. This paper discusses the estimation of shear strength parameters of soil-cement column (soilcrete) in soft clayey soil based on the relationships between the unconfined compressive and split tensile strength for the soilcrete and the effect of the jet grouting and water pressure in the values of cohesion and internal friction. For this reason, theoretical and field work models have been developed. The relation between split tensile and unconfined compressive strength results were used to draw a Mohr’s circle and failure enveloped to define the shear strength parameters of soilcrete. According to that, the results indicate that the resistance of the jet grout columns increases by increasing the nominal resistance of the grouting material (cement), water and jet grouting pressure. The shear resistance variables are increased by increasing the unconfined compressive and tensile strength of the jetting column. The value of the unconfined compressive strength ranges from (2.78-5.52 MPa). While the internal friction angle varies from 38° to 44°. On the other hand, the tensile strength is increased by increasing the unconfined compressive strength and ranges from (0.66-1.02 MPa).

Keywords: Jet grouted soil-cement columns, unconfined compressive strength and shear strength.

1. Introduction
Jet under high pressure is widely used in the industry, while in construction of civil engineering are most significantly used to cut soil structures in-situ the high velocity of jetting material are used for ground improvement [1]. Jet grouting is a soil treatment technique adopting 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 the site, before and during the construction of the final foundations [2]. When soil particles were excavated then spoil outside the hole and recouped with cementing materials such as Portland cement to create a soil cement column aspect (soilcrete) [3] Construction of spoil, which could then again be recycled or integrated on the ground works [4]. When designing jet injection columns, change in the length of the jet grout columns and soil conditions must be carefully and correctly defined [5]. Jet grouting has increasing uses in the last few years in ground improvement that has low strength, permeability and seepage problems. Jet Grouting has high potential application to decrease settlement in embankments [6]. Soft soil development technologies based on chemical effects, such as deep mixing and jet grouting are usually accepted to improve
stability when substructures are constructed in soft sediments. According to the interaction between the jet grout column installations of soil-cement reinforcing elements significantly increase the serviceability of the foundation by ways of increasing its strain features and active protection of soils from the effect of the seismic vibrations, as long as for the safe operation of the sporting structure [7]. 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 [8] [9]. The major factors that effect jet grouting columns geometry are soil property and technical parameters of the jet grouting system such as jetting pressure, size of nozzles and rotation speed during jet grouting [10].

2. Internal Friction Angle and Cohesion of Jet Grouting Column

Studies on the strength properties of soilcrete combination began as early as 1950. Established on Tri-axial shear test, Balmer (1958) initially noticed that the internal friction angle (Ø) of soilcrete mix remained constant approximately in any case of the percent of cement content. The rate of the internal friction angle Ø is 36° for fine grained soilcrete and 43° for coarse soilcrete combination. It was also established that the amount of cohesion C of soilcrete combination varied from about 241 to 3654 (kPa) depending on the cement quantity and the soil nature [11]. Mitchell (1976) suggested that the cohesion of soilcrete can be calculated approximately through the equation (1) [12]:

\[
C(kPa) = 48.265 + 0.225 q_u
\]

Where: the UCS qu is in kPa.

(Meyers et al., 2003) calculated the strength parameters of jet grouting columns structured in a firm to soft soil deposit as follows: The UCS of soilcrete was near 3.5 (MPa). According to the concrete design requirements, the tensile strength of concrete was given to be 520 times of these square root of the unconfined compressive strength of conventional concrete 0.972(MPa). The compressive and the tensile strength amounts were then used to draw a Mohr’s circle and the envelope of failure described by these circles provided the predictable soilcrete shear strength limits. Meyers et al. also noticed that C equal to 0.9 (MPa) and Ø = 34° [13]. Nikbakhtan and Osanloo, 2009 examined the effects of the clay soil properties improved by the jet grouting process before and after the processes, and the grout flow and grout pressure effects on soilcrete unconfined compression strength (UCS). The study showed that the UCS in (MPa) of soil increases logarithmically by raising the grout pressure and flow [14]. (Akinpelu, et al., 2017) researched both experimentally and analytically the relationship between the tensile strength and the compressive strength of both vibrated concrete (VC) and self-compacting concrete (SCC) of the same grades. Both kinds of concrete were designed so that the level of compressive strength of 20 (N / mm^3), 30 (N/mm^3) and 40 (N/mm^3) is achieved at 28th days. As a result, the results showed that the relation of the tensile to compressive strengths for VC and SC reduces by rising compressive strength [15].

Li and Liang (2009) [16] conducted a series of laboratory tests on silt-cement samples with an amount of cement about 20% by weight. Their test calculations exhibited that the variety of internal friction angle reaches about from 32° to 38°, which is close to the conclusions of Balmer (1958).

Significance and Use

Many different ways are used to prepare the jet grouting soilcrete and measure their properties. However, these methods are specific to site-conditions and involve several limitations in terms of jet grouting systems, varieties of native soil, and jet grouting parameters. So, the most effective way to measure jet grouting performance and soilcrete properties is by conducting a prototype model field
simulation of jet grouting in a field with the real soil condition and with actual jet grouting parameters and instruments.

Field Investigation and Soil Sampling
The site of the conducted study was located at the distance 100 m on the right bank of the Euphrates River, in an Al Nasiriyah city (375 Km southeast of Baghdad see Figure 1. The site investigation included drilling borehole 10 m in length, carrying out in-situ SPT and performing the laboratory testing of the repressive soil samples. The physical properties of the soil are represented in Table 1 to Table 3.

![Figure 1: Site Position.](image)

Table 1. Soil Description and Classification

| Depth (m) | Water table (m) from the top of B.H | Particle Size Distribution | USCS |
|----------|------------------------------------|---------------------------|------|
| [1]      | 0.0-1.0                            | [3] - [4] - [5] - [6] - [7] - [8] | Fill |
| [10]     | 2                                 |                           |
| [9]      | 1.0-2.5                            | [11] [12] [13] [14] [15] | CL   |
| [16]     | 2.5-3.5                            | [17] 2                    |
| [23]     | 3.5-4.5                            | [24] 2                    |
| [30]     | 4.5-7.5                            | [31] 2                    |
| [37]     | 7.5-9.0                            | [38] 2                    |

| γ\text{wet} (kN/m}^3 | Clay % | Silt % | Sand % | Grave l % |
|----------------------|-------|-------|--------|----------|
| [3]                  | [4]   | [5]   | [6]    | [7]      |
| [11]                 | [12]  | [13]  | [14]   | [15]     |
| [18]                 | [19]  | [20]  | [21]   | [22]     |
| [25]                 | [26]  | [27]  | [28]   | [29]     |
| [32]                 | [33]  | [34]  | [35]   | [36]     |
| [39]                 | [40]  | [41]  | [42]   | [43]     |

Clay, Silt, Sand, Grave l %, USCS
Table 2. Results for corrected SPT at the specified depth

| Depth (m) | SPT |
|-----------|-----|
| 0-1.5     | 0   |
| 1.5-3.0   | 3   |
| 4.5-6.0   | 4   |
| 9.0-10    | 11  |

Table 3. Results of Undrained Shear Strength

| Depth (m) | q unconfined (kPa) | Cu (kPa) |
|-----------|--------------------|----------|
| 1.0-2.5   | 73                 | 36       |
| 2.5-3.5   | 42                 | 21       |
| 3.5-4.5   | 76                 | 38       |
| 4.5-7.5   | 86                 | 43       |

Jet Grouting Field Design
To implement jet grouting technique, it is necessary to design and manufacture an actual jet grouting system to simulate the actual process to great soilcrete column.

Jetting Machine
This machine was designed and manufactured using iron frame and consisted of many apparatus to construct a jet grout column with the maximum vertical motion is (0.5 cm/sec) as shown in Figure 2. The mechanism of rotary units consist of the fitting the drill rod with 0.25 (horse power) gearbox motor with maximum velocity 20 (rpm).

Material and Methods
The jet grouting construction program consists of eighteen jet grout columns classified in groups. Many factors influenced the depth and diameter of a soil cement column such as jetting pressure, rod
rotation, rod vertical motion and the length to width ratio (L/d) etc. The Jet grout column diameter was 150, 200 (mm), and the total length was 2000 (mm) and the (L/d) ratio was 13.3 for the single and group columns with centre to centre clear distance (S=3D). The drilling tools generally rotated at a continuous rate 30 (rpm) to erode the soil and create column geometry. Therefore, after the erosion process is done, the high pressure of grout slurry (Portland cement and water) was 6-10 (bar) with water cement ratio (1:1) is 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 borehole by water jetting and slurry injection to build up the soilcrete was 2 (hr). The overall construction works of group are represented in Figure 3.

Figure 3: Construction steps of single and group jet grout soil-cement column (D=150 and 200 mm & L=2000 mm).

Specifications of Soil After Treated With Jet Grouting
Jet grouting is a technique for improving soil physical features. In this technique, cement slurry is injected through high pressure and rate, produces breaking of soil composition. Excavated particles of soil are then spoiling from the hole and are substituted by grout. The soil particles that stay near and into the borehole combine with grouting materials and develop soil physical characteristics. Therefore, the soil form is called “soilcrete”. Also, soilcrete has unique physical characteristics for instance, high strength, little deformability and extremely low value of permeability.

The effects of jet grouting activity on the soil properties before and after the processes can be estimated by uniaxial compression strength (UCS). After completing the pile load test process a series of core barrel samples were taken from different depth of jet grouting columns by using the continued Coring method. Based on the results of the unconfined compressive test a total 18 samples in different ages, including 1, 6, 12 (month) were used for analysis of strength of jet grouting columns. The average of unconfined compression strength of jet grouting soil cement column results is illustrated in Table 4. Therefore, the result shows that the jet grouting produces an increase in unconfined compression strength of the soil.

Table 4: Specification of Core Jet Grouting Samples

| Age of curing (month) | Jetting Pressure (Bar) | Jet grouting column diameter (mm) | Number of samples | Average Unconfined compressive strength qu (N/mm²) |
|-----------------------|------------------------|----------------------------------|-------------------|-------------------------------------------------|
| 1                     | 75                     | 150                              | 3                 | 2.78                                            |
| 6                     | 75                     | 150                              | 3                 | 3.33                                            |
| 12                    | 75                     | 150                              | 3                 | 4.21                                            |
| 1                     | 125                    | 200                              | 3                 | 3.67                                            |
The strength properties of the jet grouting columns are represented by the cohesion and internal friction angle. In other words, the compressive strength of jet-grouting cement soil is the important step for the design of jet grouting functions progress. Different methods have been used to estimate the cohesion and internal friction angle. The relationship between the split tensile and the compressive strength results will be used to draw Mohr’s Circles and failure enveloped even to estimate the shear strength parameters. According to that there are a lot of Mohr’s Circles that can plotted according to the values of unconfined compression test for jet grouted column that is explained in Table 4. The results of tensile strength based of many theories are illustrated in Table 5 and Mohr’s Circles and failure enveloped in Figure 4. The shear strength (Cu) and internal friction of jet grouting column can represented in Table 6 based on Mohr’s Circles theory and other methods.

| Average Unconfined compressive strength q_u (N/mm2) | ACI Committee 318 (2014)[17] | CEB-FIb(1991)[18] | Carino and Lew (1982)[19] | Oluokun et al. (1991)[20] | Arioglu et al. (2006)[21] | Lavanya and jegan (2015)[22] | Average Tensile Strength (N/mm2) |
|---------------------------------------------------|-----------------------------|-------------------|--------------------------|--------------------------|---------------------------|-----------------------------|-----------------------------|
| Split Tensile Strength (N/mm2)(T)                  | T1 = 0.56* *qu<sup>0.5</sup> | T2 = 0.3* *qu<sup>0.66</sup> | T3 = 0.272* *qu<sup>0.71</sup> | T4 = 0.294* *qu<sup>0.89</sup> | T5 = 0.387* *qu<sup>0.63</sup> | T6 = 0.249* *qu<sup>0.72</sup> |               |
| 2.78                                               | 0.93                        | 0.59              | 0.56                     | 0.60                     | 0.74                      | 0.55                        | 0.66                        |
| 3.34                                               | 1.02                        | 0.66              | 0.64                     | 0.67                     | 0.83                      | 0.63                        | 0.74                        |
| 4.21                                               | 1.15                        | 0.77              | 0.75                     | 0.79                     | 0.96                      | 0.76                        | 0.86                        |
| 3.68                                               | 1.07                        | 0.71              | 0.68                     | 0.72                     | 0.88                      | 0.68                        | 0.79                        |
| 4.62                                               | 1.20                        | 0.82              | 0.81                     | 0.85                     | 1.01                      | 0.81                        | 0.92                        |
| 5.52                                               | 1.32                        | 0.93              | 0.91                     | 0.96                     | 1.14                      | 0.93                        | 1.02                        |

The process of jet grouting is influenced by several parameters of the soft soil and the jet grouting method, the effects on the soil properties before and after jetting, and the influences of jetting pressure, age of curing and unconfined compression strength of soilcrete’s strength. According to the data results obtained from field and experiments, it can be concluded that:

1- Unconfined compression results of soil treated by jet grouting column increase with increasing the jetting pressure as shown in Figure 5 and Figure 6. Thus, these results are in line with (Nikbakhtan and Osanloo, 2008), as explained above.

2- Unconfined compression results of soil treated by the jet grouting column increase with increasing average tensile strength of the jet grouting soilcrete as shown in Figure 7. These results are in line with (Akinpelu, et al. 2017).

3- The average cohesion results of soil treated by jet grouting increase with increasing average unconfined compressive strength of soilcrete as shown in Figure 8, and it can be concluded that the results are in good agreement when compared to the field cohesion of soilcrete based on Mohr’s Circle with experimental equations explained by Mitchell, 1976.
Figure 4: Estimation of shear strength of jet grouted soil cement column from compressive strength and split tensile strength.

### Table 6: Evaluation of the shear strength ($c_u$) and internal friction ($\phi$) of jet grouting column.

| Average Unconfined compressive strength $q_u$ (N/mm$^2$) | Average Split Tensile Strength (N/mm$^2$) | Pressure (bar) | Column Diameter (mm) | Age (month) | Angle of friction ($\phi$) degree | Cohesion ($c_u$) (N/mm$^2$) |
|----------------------------------------------------------|------------------------------------------|----------------|----------------------|-------------|-----------------------------------|--------------------------|
| [77]                                                      | [76]                                     | [75]           | [74]                 | [73]        | [72] M [71] M [70] M [69] M      |                          |
Figure 5: Relationship between water jetting pressure and average unconfined compressive strength.

Figure 6: Relationship between grout jetting pressure and average unconfined compressive strength.
Conclusion

Although the use of jet grouting in the last few years is very common in foundation constructions, an estimated strength of soil-cement column is still based on simple assumptions that often come from accumulated deep foundations practice. Field work studies can be characteristic of jet grout soil-cement column response to certain interactions with the surrounding soil, effect of jet grouting operation parameters and grouting materials because of facility difficulties, dimensions, physical and mechanical properties of jet grout columns. As a result, the effects of jet grouting method on the soil properties before and after the processes can be estimated by uniaxial compression strength (UCS). Therefore, the result shows that the jet grouting produces an increase in unconfined compression strength of the soil from (36-40) kPa to average (4) MPa.

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