Jet grouting technique and strength properties of jet grout columns

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Abstract. Jet grouting is a relatively recent development which is applied for mainly ground improvement purposes and provides effective solutions to many geotechnical and geoenvironmental problems. Jet grouting technique differs substantially from the other grouting techniques in that this technique can be used in treating a wide range of soil types. Therefore the application fields of jet grouting are rapidly increasing. The main emphasize in this paper is given to the strength properties of jet grout columns. The strength properties of jet grout columns is investigated by the example of five case studies. The subsoil conditions and foundation engineering evaluations of the investigation areas are presented in the case studies. The strength properties are investigated by referring to the unconfined compressive strength test results of the core samples obtained from jet grouting columns.

1. Introduction
Jet grouting involves a method of displacing and instantaneously mixing the subsoil with a mortar grout to produce hard, impervious columns, panels or wings. In this method the ground is mixed in situ directly with a stabilizer (a mixture of water and cement usually), which is injected at a very high pressure (300 bar at least) [1]. By jet grouting technique the mechanical characteristics of the subsoil is improved which results in an increase in the bearing capacity and modulus of elasticity. The jet-grout columns can be used also for impermeable barriers. Jet grouting is a very versatile technique because it can be applied not only vertical but also oblique or even horizontal [2]. Jet grout columns are used primarily to improve bearing capacity and reduce settlements of foundations on soft soils under static loading. However, jet-grout columns also will change the response of soft soil layers subjected to earthquake loading [3]. It must be also mentioned that jet grout columns can be used as a mitigation method for soils that have a potential to liquefy under earthquake loading conditions [4].

The high speed of the grout mixture, coming out of the nozzle/s, destroys the natural structure of the soil and creates a mixing between the ground and the stabilizer. The result is a homogeneous and continuous structural element with predetermined characteristics [1]. Jet grouting technique offers the possibility of treating a range of soils from gravel to clay and a valuable alternative to conventional and other soil improvement methods [5, 6].

The strength properties of jet grout columns is a major parameter in the design of soil improvement schemes and hence there is the need to estimate the strength of the jet-grout columns beforehand.

This study covers five case studies of jet-grout applications in order to reach some conclusions about the strength properties of jet grout columns. The detailed case studies which are used in this paper are as follows:

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1. A soil improvement work by jet grout columns to minimize the settlements and to mitigate liquefaction potential in Carrefour/Izmit Hypermarket and Shopping Center area, which will be called Site-1.

2. A soil improvement work by jet grout columns to increase bearing capacity and to mitigate liquefaction potential in Kadir Has University Campus area in Selimpasa-Istanbul, which will be called Site-2.

3. A soil improvement work by jet grout columns to mitigate liquefaction potential in Casaba housing project area in Omerli - Istanbul, which will be called Site-3.

4. A soil improvement work by jet grout columns to increase bearing capacity, to mitigate liquefaction potential and to minimize the settlements in ALEV (Avusturya Liseliler Vakfi) High School Area in Omerli - Istanbul, which will be called Site-4.

5. A soil improvement work by jet grout columns against settlement of a petroleum tank of Petrol Ofisi A.S. in Haramidere - Istanbul, which will be called Site-5.

2. Jet grouting technique
Jet grouting is the youngest major category of grouting for ground treatment. The ASCE Geotechnical Engineering Division Committee on Grouting (1980) defined jet grouting as a "technique utilizing a special drill bit with horizontal and vertical high speed water jets to excavate alluvial soils and produce hard impervious columns by pumping grout through the horizontal nozzles that jets and mixes with foundation material as the drill is withdrawn" [7]. The jet grout execution is schematized in figure 1 and the jets used demonstrated in free air is seen in figure 2.

Jet grouting offers a radically different approach, employing erosion to enable grouting to proceed across a very wide range of soil types. The technique employs high pressure erosive jets of water or grout to break down the soil structure, removes varying proportions of the resultant soil particles and replaces them with cement-based grouts placed during the erosive operation. Soil particles not removed become mixed with the grout in situ to form the treated mass. Experience worldwide has now proved the important advantage of the technique in enabling the treatment of soils with simple cement grout almost regardless of grading and structure [8, 9, 10]. Soil particles not removed become mixed with the grout in situ to form the treated mass and the Keller Group refers to this material as Soilcrete, to identify it as the product of jet grouting and to correctly distinguish it from the injected grout.
Jet grouting may be done in pre-drilled boreholes or they can be self-drilled by attaching drill bits, appropriate to the ground conditions, to the monitor base. Selection or pre-drilling versus self-drilling is dictated by the soil or rock types to be penetrated, by the balance of drilling time versus jetting time, or by other factors such as working space limitations.

The dimensions of the so obtained elements depend on the nature of the soil and the choice of operating parameters such as rotation speed, lifting speed of the rods, pressure and flow rate of the injection fluids, diameter and number of the employed nozzles.

Despite all the ongoing developments and refinements, there are basically only three methods that are being used, and these may be generically classified as one, two or 3 fluid system. These three basic methods will be discussed a little bit more in detail below.

**One-Fluid System (JET1):** The fluid is grout, and in this system the jet simultaneously erodes and injects. The concept of the nozzle is shown in figure 3. It involves only partial replacement of the soil. It is the most simple and widespread jetting method, experimented in Japan at the beginning of the 1970s and developed in Italy in the mid-1970s. In this simplest form of jet grouting a hollow stem grouted pipe fitted with one or several nozzles of 2.0-4.0 mm diameter is positioned at the treatment depths. Grout is forced into the ground through the nozzles at pressures as high as 600 bars, thus simultaneously eroding the soil and placing grout. The process is continued by lifting and rotating the monitor at a constant rate in any stratum to create a column of treated soil consisting of a mixture of the injected grout and eroded soil. The diameters of Soilcrete columns obtained with this method are different according to the ground and operating parameters but range approximately between 600-800 mm in clay and up to 1000 mm in granular soils [1, 8].

![Typical single tube jet nozzle](image3.png)

**Figure 3.** Typical single tube jet nozzle [13].

**Two-Fluid System (JET2):** This method uses a cement jet inside a compressed air cone. This stem gives a larger column diameter than one-fluid system and gives a higher degree of soil replacement. This is a more advanced form of the one-fluid system in which the erosive effect of the grout jet is
considerably enhanced by the addition of a shroud of compressed air. This enables a greater treated volume during each jetting lift when compared with the single jet approach. The jetting pipes for the two-fluid system consist of two concentric hollow stem pipes. The grout flows in the inside pipe, as in the Jet 1 technique, while the compressed air flows in the outside pipe with pressure varying from 8 to 12 bars. The presence of air entails a considerable reduction in friction loss of the kinetic energy of the grout jet, so that diameters exceeding 60-80 per cent compared to Jet 1 technique are obtained [1, 8].

**Three-Fluid System (JET3):** Here, an upper ejection of water inside an air envelope is used for excavation, with a lower jet emitting grout for replacement of jetted soil [14]. This system uses air-shrouded water jetting for soil erosion and separate injection nozzles for placement of the grout. This arrangement, needs a concentric triple pipe for separately phasing of air, water and grout. The injection of the three fluids permits more soil to be removed from the ground and therefore, this system can be used as a full replacement of the in situ soil with grout. The system enables achievement of a wider range of geotechnical performance form treated soil. In this system the water with pressure of 400-600 bar flows in the inside pipe. The compressed air gets into the intermediate pipe at pressure of 8-12 bar. Water and air go out from nozzles as in Jet 2. In the outside pipe the grout of cement flows with pressure varying from 30 to 80 bars; it is injected into the ground through nozzle/s, situated just under that suitable for the going out of the air/water mixture. The column sizes formed using the three-fluid system are usually the largest in diameter due to the separate injection of air/water and grout. The column sizes in sands vary from 500 to 3000 mm, and in clays 500 to 1500 mm [1, 8, 15]. The principals of all three jet grout methods are shown in figure 4.

![Figure 4](image-url)  
**Figure 4.** Variants of jet grouting process.

### 2.1. Design aspects

The physical properties of the Soilcrete are a function of the in situ properties of the soil before treatment, the properties of the grout and the operational parameters of the jetting.

The standard water/cement ratio is 1 and its specific gravity is 1410-1570 kg/m³. This ratio varies depending on the employed method, the type of required improvement and on the required final strength of the columns. Dosages with water/cement ratio lower than 0.7 are generally not employed, except when bentonite mixtures are used to produce waterproof plastic grout curtains. The quantity of cement per m³ of treated soil varies between 350 and 700 kg/m³, and 450 kg of cement per m³ of treated ground is usually the average value employed [1, 14, 16, 17].

The choice of the operational parameters depends on the ground, the diameter of the column, the bearing strength required and on the adopted system. The main operational parameters are: Injection pressure; Influence of nozzle size, Type and quantity of grout; Monitor rotation and withdrawal rates. Specialist geotechnical contractors have various methods of balancing these factors to match design requirements with their experience and equipment [12]. Regarding these range of variables and the complexity of natural soils, it is not surprising that no fundamental theoretical relationships governing jet grouting have been produced. The selection of parameters to be used is guided by experience and
enhanced by semi-empirical relationships. Here we will try to summarize the main parameters effecting the jet grout column.

2.1.1. Injection pressure

Injection pressure is the most important parameter in obtaining the required column diameter. The ideal injection pressure is determined according to past experience and from in-situ tests. This factor is also a function of the capacity of the high pressure pump and of the nature of the soil.

The injection pressure values can be classified as follows:

- **Low**: pressure between 200 and 250 bar
- **Medium**: pressure between 300 and 400 bar
- **High**: pressure between 400 and 700 bar

In general high pressure results in larger diameter, however this is not always the case. Sometimes the employed energy does not correspond to a suitable increase in the diameter of the column. The diameter of the column is also a function of the time of jet grouting for a single column. The speed of rotation of the head and withdrawal rate, hence processing time assures that the required diameter is reached homogeneously [1, 18]. In reality the true radius of a jet is reduced from the theoretical because of the dampening effect of the relatively dense water/soil slurry. This is particularly true in cohesive soils where considerable energy has to be consumed simply disrupting the soil structure and a minimum jetting pressure of 40 MPa may be needed just to erode a soil of 40 kPa shear strength.

2.1.2. Influence of nozzle size

Nozzle design is crucial to the success of jet grouting because nozzle energy and grout flow are functions of nozzle diameter and injection pressure. The nozzles which are placed in the monitor are responsible for the velocity of the jet. The nozzle diameters vary from 1.5 to 8 mm. Details of ideal nozzles are provided by Shizabaki and Ohta [13]. The dispersion of the grout increases when the diameter of the nozzles is decreased. Experiments conducted in former Soviet Union, Broid et al. (1981) demonstrated that large-diameter (5 to 7 mm) and high-discharge (120 to 250 liters/min) nozzles doubled grouted volume in sandy soils at low pressures (7 MPa) as compared to Japanese experience [14, 15].

2.1.3. Monitor rotation and withdrawal rates

In order to obtain an effective mixing of the ground with the stabilizer, the rotation speed of the rods has to be rather slow and the lifting speed has to lead to a homogeneous distribution of the jet in the treated area. The lifting time of the rods depend on the type of ground and on the quantity of mixture to be injected. Cohesive soils usually require longer time to obtain an effective breaking action of the jet and a suitable mixing of the ground with the stabilizer. The rotation and lifting speed depend on the adopted jetting method and as a consequence on the volume of the ground to be treated. The lifting of the rods happens by step of 2-8 cm, but the experiences have shown that a 4 cm step is the most appropriate value. JET 2 and JET 3 systems have longer process time compared to JET 1 system because by these systems larger diameters are obtained and greater volume of the ground is treated. The rotation speed usually varies between 10 and 20 rpm and sometimes reaches 30 rpm.

When time of exposure of the jet is considered, a design curve of the type shown in Figure 5 is obtained. Increased pressure or decreased lifting speed increases column diameter. Variation in column diameter rarely exceeds 10 per cent except in very coarse soils. [1, 8, 14].
Welsh et al. (1986) summarized the rules of thumb regarding the relation between soil type and Soilcrete characteristics [19]:

- For any soil, grout or water pressure and probe withdrawal rate are the most significant design factors impacting the volume of jet grouted soil.
- For any given grout pressure and withdrawal rate, jet grouted volume decreases with increasing clay content.
- As clay content increases, grout pressure must be increased and/or withdrawal rate decreased for a given jet grouted volume.
- It is difficult to obtain jet grout diameters in excess of 1.5 m in stiff to hard clays using typical grout or water pressures.
- Jet grouted volume is not significantly affected by grain size distribution if the uniformity coefficient ($D_{60}/D_{10}$) is equal to or greater than 8.
- If the uniformity coefficient for granular soils is less than 8, column diameters up to 3 m are possible using typical operating parameters.
- If the gravel size and larger particle content of the soil is greater than 50 per cent, grout penetration may be reduced and be more irregular, owing to the tendency for large particles to reflect the jetstream.

3. Properties of jet grout columns

Grouts used in jet grouting need to be pumpable over distances of up to 100 m and at very high pressures in the case of the one and two-fluid systems. They are mixed in situ with the soils being treated to an extent determined by the system and jetting parameters selected. For these reasons and on grounds of cost, simple cementitious grouts have been used. Where strength or stiffness is the main requirement, cement grouts with water cement ratios as low as 0.6 have been employed. Small percentages of bentonite have been added as anti-bleed agents where required and pulverized fuel ash (PFA) has also been used as a partial cement replacement to reduce costs. Cement-bentonite mixes are usually employed when low permeability is paramount. These have higher water/cement ratios up to 2.0 and bentonite contents up to 10 per cent by weight of cement [10, 12].

Strength of jet grout columns is usually assessed on the basis of compressive strength data. These are measured directly using laboratory unconfined compression tests on samples obtained by coring. The core samples are obtained at least 28 days after the formation of the column and the
height/diameter ratio of the sample should be at least two. Unconfined compression tests are performed by exerting the load under constant rate (approximately 1 mm/min). Minimum three samples should be tested [8, 15, 20].

The deformability of Soilcrete is also a parameter used in the design and the Elastic modulus is even more variable than strength but in general the modulus/strength (E/R) ratio increases with strength from about 300 to over 1000. Figure 6 shows secant modulus E at 40 per cent peak strength versus compressive strength form tests in various Soilcretes from the Milan alluvia’s. For the same value of unconfined compressive strength, the modulus of elasticity value may vary by a factor of 2 to 3. This also occurs in sandy formations where there is a slight silt content and where unconfined compressive strength may be up to 28 MPa. Modulus of elasticity values have ranged from 2500 to 6500 MPa. Furthermore Tinoco et al (2014) state that Young’s modulus of jet grout column can be predicted from a combination of Unconfined Compression Strength, the volumetric content of cement, age of the mixture and the soil properties (particularly its clay content) [21].

![Figure 6. Secant modulus versus strength [14].](image)

4. Case Studies In Turkey
In order to study the strength properties of jet grout columns in various ground conditions some examples of jet grouting applications in Turkey are taken into consideration. The main concern of this study is the strength properties of jet grout columns. The operational parameters used in the construction of all 5 cases are given in table 1. As can be seen, in all cases JET 1 method of installation has been utilized. Also other parameters are relatively similar, which allows a comparison of the Soilcrete strength results.

| Site     | Unit | Site 1 | Site 2 | Site 3 | Site 4 | Site 5 |
|----------|------|--------|--------|--------|--------|--------|
| Injection pressure | Bar  | 450    | 450    | 450    | 450    | 450    |
| Type of nozzles    | Type 1 | Type 1 | Type 1 | Type 1 | Type 1 | Type 1 |
| Number of nozzles  | -2    | 2      | 2      | 2      | 2      | 2      |
| Diameter of nozzles | mm    | 2      | 2.0    | 2.2    | 2.2    | 2.4    |
| Rotation speed of rods | RPM   | 20     | 25     | 16     | 16     | 20     |
| Lifting speed of rods | sec/m | 120    | 130    | 100    | 100    | 160    |

The case studies which will be discussed in this section are as follows.
4.1. Site 1
The structures consisted of a single-story shopping center main building and the parking garage. According to the settlement analysis, excessive settlements were calculated under the buildings. Jet grouting technique was chosen as a solution for these problems and to improve the properties of the site soil. The total number of jet grout columns was 3778 having 9 m length and 60 cm diameter. The site is located on a marine sedimentary plain. There was no major elevation difference throughout the site. The region is represented by marine quaternary aged sediment which consists of clay, silt and sand. Within the construction site, 17 borings, 15 CPT and 4 trial pits were performed. Based on the results of boreholes, CPT and trial pits the subsoil within the site was (from base to top) silty clay, sand and approximately 3 m thick fill containing sand and gravel. The groundwater elevation was observed at approximately 2.5 m below the ground level [22]. Laboratory tests were conducted on disturbed and undisturbed soil samples which were recovered from borings and trial pits. Based on the results of soil borings, CPT results and laboratory test results, one representative soil profile was accepted for the entire investigation area. This idealized soil profile is given in table 2. After stripping the existing 2.50 m thick top uncontrolled fill material at the ground surface, the site would be brought to the same level by placing a controlled fill.

| Depth     | Geological Unit                  | Geotechnical Parameters         |
|-----------|----------------------------------|---------------------------------|
| 0.00-2.50 | Artificial fill                  | $\phi = 30^\circ$               |
|           |                                  | $SPT \ N > 50$                  |
| 2.50-5.50 | Medium stiff Silty Clay          | $w_a = 30-35\%$                |
|           |                                  | $\phi = 25^\circ$               |
|           |                                  | $\gamma_n = 18 \ kN/m^3$        |
|           |                                  | $SPT \ N_{ave} = 5$             |
| 5.50-10.00| Fine-medium, clayey, loose-medium dense Sand | $SM-SP$                      |
|           |                                  | $q_c = 5.0 \ MN/m^2$            |
|           |                                  | $\gamma_n = 18 \ kN/m^3$        |
|           |                                  | $\phi = 35^\circ$               |
| +10.00    | Medium stiff-stiff Silty Clay    | CH-MH                           |
|           |                                  | $w_a = 50\%$                   |
|           |                                  | $\phi = 25^\circ$               |
|           |                                  | $\gamma_n = 18 \ kN/m^3$        |

Table 2. Idealized soil profile for Site 1 [22].

The water/cement (w/c) ratio was kept constant as one and Portland cement (PC) 42.5 was used. In order to determine the resulting compressive strength of jet grout columns thirteen core samples were obtained from the jet grout columns in the investigation area.

Soil improvement by jet grouting was successfully employed in this project in order to overcome problems related with settlements and liquefaction. The investigation area is located in the main earthquake zone of Turkey and it was important how the jet grout columns would behave in case of an earthquake. After the 17th August 1999 earthquake it was observed that jet grout columns have done their job very well.

The results of the unconfined compression tests applied on core samples showed a wide variation. The unconfined compressive strengths were between 1.54 MPa and 6.70 MPa. The variation was due to the non-homogeneous characteristic of the soil layers and the variable thicknesses of clay and sand.
layers. The higher compressive strength values are obtained from the jet grout columns constructed in sand dominant regions.

4.2. Site 2
This case study reports a jet grouting application in Istanbul. The aim of the jet grouting application for the new building on the site was to improve the bearing capacity of the foundation soil and to mitigate the liquefaction potential. The subject area is in the first degree seismic zone and the existing building on the same site has been damaged after the 17th August, 1999 Earthquake. The foundation soil of the existing building was to be improved by jet grout columns in order to increase the bearing capacity and to mitigate the liquefaction potential.

In the new building area a total number of 668 jet grout columns with 60 cm diameter and an average length of 9 m were executed. In the existing building area the total number of jet grout columns was 774 having 8.5 m length and 60 cm diameter [23].

The site is located just beside the sea shore and there is no major elevation difference throughout the site. The subject area is represented by fill and alluvium layers followed by oligogen aged sandstone-siltstone-mudstone layers. The alluvium layer is composed of sand and clay layers in various thicknesses.

Within the construction site, 5 borings and 2 CPT were performed in the new building area and 4 borings were performed in the existing building area. The groundwater elevation was observed almost at the surface since the area is located just beside the sea [24].

Based on the results of soil borings, CPT results and laboratory test results, one idealized soil profile was created which is given in table 3.

After stripping the existing 2.00 m thick top uncontrolled fill layer, the site would be brought to the same level by placing a controlled fill.

Table 3. Idealized soil profile for Site 2 [24].

| Depth     | Geological Unit                  | Geotechnical Parameters |
|-----------|----------------------------------|-------------------------|
| 0.00-2.00 | Artificial fill                  |                         |
| 2.00-3.50 | high content of plastic, organic material; soft Clay-Silt | ML-CH c_u = 2.5-3.7 t/m² LL = 80 % | |
|           | SPT N = 3-4                      |                         | |
|           | γ_n = 1.75 t/m³                  |                         | |
|           | φ = 0°                           |                         | |
| 3.50-8.00 | Marine originated , loose-medium dense Sand | SM-SP c_u = 0 | |
|           | SPT N = 7-17                     |                         | |
|           | γ_n = 1.80 t/m³                  |                         | |
|           | φ = 30°                          |                         | |
| >8.00     | Siltstone-Mudstone               |                         | |
|           | SPT N > 50                       |                         | |
|           | γ_n = 2.00 t/m³                  |                         | |
|           | φ = 43°                          |                         | |
|           | c = 1 t/m²                       |                         | |

The water/cement (w/c) ratio was kept constant as one and Portland cement (PC) 42.5 was used.

Unconfined compression tests were done on specimens obtained by core sampling 28 days after their construction. The specimens had a diameter of 11.5 cm and a length/diameter ratio of only 1. Two samples from each column were tested and the average value for these two samples was accepted as the unconfined compressive strength value for that column. Altogether four core samples were obtained from the test jet grout columns in the investigation area.

The aim of soil improvement in this project was to increase the bearing capacity and to prevent the liquefaction potential. The results of the unconfined compression tests applied on core samples were close to each other and an average unconfined compressive strength of 3.5 MPa was obtained. The soil
profile did not represent much variations over the site and due to this reason the compressive strength values were in a close range.

4.3. Site 3

This case study reports the large jet grouting application in a housing project in Istanbul. The project consisted a large number of two-story villas. According to the bearing capacity and settlement analysis, no problems were expected regarding these two criteria. But due to the liquefaction potential of the sand layers in a large part of the subject area jet grouting technique was chosen. The diameter of jet grout columns were 60 cm and lengths were varying between 7-14 m adding to a total of 72415 m of jet grout columns.

The subject area is located in the Valley of Riva River. The main soil type throughout the area is alluvium layer composed of sand and clay layers which was sedimented by Riva River. The clay layers of the alluvium is low plasticity clay and the sand layers are fine and medium grained. The thicknesses of these layers are variable throughout the site. As a general property in the site, the upper 10-15 m layers are soft and loose. The undrained shear strength values are low and compressibility values are high. The deeper layers are composed of more stiff clay layers and turf. The groundwater level is just below or at the ground level in the investigation area.

Although it is difficult to represent the soil profile in the area by just one idealized soil profile since the soil layers have different thicknesses throughout the area, based on the results of soil borings and referring to the soil investigation reports prepared for the subject area, one representative soil profile was prepared for the entire investigation area. This profile would give an idea about the general geology of the site. This idealized soil profile is given in table 4.

| Geological Unit | Geotechnical Parameters |
|-----------------|-------------------------|
| Gravelly, silty, sandy soft Clay | SPT $N_{ave} = 3$ $\phi = 2^\circ$ $c_u = 5 \text{ t/m}^2$ $w_n = 15-25\%$ $PL = 15-25\%$ $LL = 25-35\%$ $PI = 5-20\%$ |
| Gravelly, clayey sand, loose-medium dense Sand | SPT $N = 6-15$ $\gamma_n = 1.80 \text{ t/m}^3$ $\phi = 30^\circ$ $\gamma_n = 2.00 \text{ t/m}^3$ |
| Stiff clay layer | SPT $N > 50$ |

The water/cement (w/c) ratio was kept constant as one and Portland cement (PC) 42.5 was used.

In order to determine the resulting compressive strength of jet grout columns three core samples from one representative jet grout column in each villa site were obtained. The distribution of the unconfined compressive strength values are shown in figure 7. The results of the unconfined compression tests applied on core samples gave a wide range of values as in Site 1. That is because the soil profile over the site showed different characteristics and variable thicknesses of sand and clay layers were encountered. Referring to figure 7 it can be said that the general unconfined compressive strength values are distributed between 2.5 and 3.5 MPa.
With appropriate operating parameters the soil improvement job was successfully completed and improved soil was tested by CPT in order to make a comparison between before and after treatment with jet grout columns.

4.4. Site 4
The subject area is just next to Site-3 reported above, so similar geological characteristics are observed throughout the site. Within the construction site, 9 borings were performed and according to the results of these borings the main soil type throughout the area is determined as an alluvium layer composed of sand and clay layers which is sedimanted by Riva River. The thickness of soft and loose alluvium layer is about 16 m and below this layer there exists a layer of 2 m thick gravel and as the bearing strata consolidated clay and claystone layers.

The groundwater level is just below or at most 1 m below the ground level in the investigation area.

Based on the results of soil borings, and laboratory test results, one representative soil profile was accepted for the entire investigation area. This idealized soil profile is given in Table 5.

Since the thickness of weak alluvium layer was different throughout the site, the column lengths were also variable between 9-11.5 m based on the depth of the liquefiable soils. The diameter of jet grout columns were 60 cm and the total length of jet grout columns installed on this site was 18,398 m.

The water/cement (w/c) ratio was kept constant as one and Portland cement (PC) 42.5 was used.

In order to determine the resulting compressive strength of jet grout columns, core samples were obtained from fourteen jet grout columns. The unconfined compression tests were conducted on specimens obtained by core sampling 28 days after their construction. The experiments were applied to the specimens of 9.5 cm diameter and length/diameter ratio 2.
Table 5. Idealized soil profile for Site 4.

| Depth   | Geological Unit                  | Geotechnical Parameters |
|---------|---------------------------------|-------------------------|
| 0.00-6.00 | Silty, slightly fine sand content, soft-medium stiff, Claysilty         | $\gamma_n = 1.90 \text{ t/m}^3$ |
|         |                                 | $\phi = 0^\circ$         | $w_n = 29\%$ |
|         |                                 | $c_u = 7 \text{ t/m}^2$  | $\phi = 0^\circ$ |
| 6.00-8.00 | Silty, clayey, fine grained, loose Sand                       | $SPT N_{ave} = 7$        |
|         |                                 | $\gamma_n = 1.80 \text{ t/m}^3$ | $c_u = 0$ |
| 8.00-14.50 | Silty, fine grained sand and gravel content, soft-medium stiff Clay     | $SPT N_{ave} = 12$        |
|         |                                 | $\gamma_n = 1.90 \text{ t/m}^3$ | $w_n = 29\%$ |
|         |                                 | $\phi = 0^\circ$         | $\phi = 30^\circ$ |
| 14.50-18.00 | Medium-coarse grained, sand-gravel mixture, medium stiff-stiff Sand-Gravel | $SPT N_{ave} = 20$        |
|         |                                 | $\gamma_n = 1.85 \text{ t/m}^3$ | $w_n = 25\%$ |
|         |                                 | $\phi = 30^\circ$        | $\phi = 35^\circ$ |
| 18.00   | Claystone-Siltstone              | $SPT N > 50$             |
|         |                                 | $\gamma_n = 2.00 \text{ t/m}^3$ |

The jet grouting application was completed successfully and no problems have been encountered in the buildings.

4.5. Site 5

This case study reports the jet grouting application in a petroleum tank farm area in Istanbul. The subject area is located in the potential landslide zone and the stability of the foundations should be maintained. The aim of the jet grouting application for the ground improvement was to increase bearing capacity for the tank foundation, to avoid the risk of differential settlements and to preserve the slope stability in the subject area.

The diameter of jet grout columns were 80 cm and lengths were 18 m adding to a total of 2700 m.

Within the construction site, 11 borings were performed and according to the results, the geological layers in the subject area are determined. The investigation area is located in a potential landslide zone and due to this reason different soil layers are encountered in various thicknesses. The base layer in the area is oligosen aged and is composed of sand, sandstone and clay layers. The dominant lithology is gravelly, plastic, consolidated clay. Above this layer as a result of being in the landslide zone, the soil layers of different lithology and thicknesses can be observed. These layers are Gungoren, Cukurcesme and Bakirkoy formations. Gungoren formation is generally composed of green clay, silt and clay containing lime. Sand layers are also observed. The upper layers of Cukurcesme formation is represented by fine sand and gravel whereas in the lower layers thin clay layers can be seen. The uppermost layer is Bakirkoy Formation composed of white-grey colored soft limestone and green-grey colored clay. Sand layer can also be observed similar to Gungoren formation [27].

Based on the results of soil borings, and laboratory test results, one representative soil profile was accepted for the tank area where jet grouting was applied. This idealized soil profile is given in Table
6. Some of the geological units told in the previous section are not encountered in this tank area. The upper layer is almost 5 m thick fill layer and below it there is the landslide fill layer. This part of the investigation area shows worse characteristics from the point of bearing capacity compared to the whole investigation area [27].

Table 6. Idealized soil profile for Site 5.

| Depth     | Geological Unit                        | Geotechnical Parameters |
|-----------|----------------------------------------|-------------------------|
| 0.00-5.00 | Slightly fine sand content, medium stiff Clay | CH-ML                  |
|           |                                        | SPT \(N_{ave} = 8\)    |
|           |                                        | \(\gamma_n = 1.70 \text{ t/m}^3\) |
|           |                                        | \(\phi = 0^\circ\)    |
|           |                                        | \(c_u = 5 \text{ t/m}^2\) |
|           |                                        | \(w_n = 27\%\)        |
|           |                                        | \(\text{LL} = 55\%\)  |
|           |                                        | \(\text{PL} = 22\%\)  |
|           |                                        | \(\text{PI} = 33\%\)  |
| 5.00-9.00 | Silty, clayey, fine grained gravel content, loose Sand | SM-SP                  |
|           |                                        | SPT \(N_{ave} = 8\)    |
|           |                                        | \(\gamma_n = 1.70 \text{ t/m}^3\) |
|           |                                        | \(\phi = 28^\circ\)    |
|           |                                        | \(c_u = 0\)            |
|           |                                        | \(\text{LL} = 73\%\)  |
|           |                                        | \(\text{PL} = 38\%\)  |
|           |                                        | \(\text{PI} = 35\%\)  |
| 9.00-17.00| Little clay and silt content, fine grained, dense Sand-Gravel | CL-ML-CH               |
|           |                                        | SPT \(N_{ave} = 21\)   |
|           |                                        | \(\gamma_n = 1.61 \text{ t/m}^3\) |
|           |                                        | \(\phi = 0^\circ\)    |
|           |                                        | \(c_u = 8 \text{ t/m}^2\) |
|           |                                        | \(w_n = 45\%\)        |
|           |                                        | \(\text{LL} = 60\%\)  |
|           |                                        | \(\text{PL} = 39\%\)  |
|           |                                        | \(\text{PI} = 21\%\)  |
|           |                                        | \(w_n = 45\%\)        |
| +17.00    | Silty, hard Clay                        | ML-MH                  |
|           |                                        | SPT \(N_{ave} = 39\)   |
|           |                                        | \(\gamma_n = 1.75 \text{ t/m}^3\) |
|           |                                        | \(\phi = 0^\circ\)    |
|           |                                        | \(c_u = 15 \text{ t/m}^2\) |
|           |                                        | \(\text{LL} = 49\%\)  |
|           |                                        | \(\text{PL} = 33\%\)  |
|           |                                        | \(\text{PI} = 16\%\)  |
|           |                                        | \(w_n = 28\%\)        |

The column lengths were determined by considering the slope stability analysis for the investigation area and was decided to be 18 m. The water/cement \((w/c)\) ratio was kept constant as one and Portland cement (PC) 42.5 was used.

In order to obtain the unconfined compressive strength values, three samples from each column were tested and the average value for these three samples was accepted as the unconfined compressive strength value for that column.

The results of the unconfined compression tests applied on core samples were found to be 4.8 MPa as an average value. Comparing to the other cases the higher strength value is result of higher SPT blow counts in the area and larger column diameter.

5. Effect of grain size distribution on jet grout column strength

In jet grouting technique, jet grout columns are formed by the in situ mixing of the ground with a mixture of water and cement like plain concrete. However concrete is a composite material which consists essentially of a binding medium within which are embedded particles or fragments of a
relatively inert mineral filler. In Portland cement concrete the binder or matrix, either in the plastic or in the hardened state, is a combination of Portland cement and water; it is commonly called the "cement paste." The filler material, called "aggregate", is generally graded in size from a fine sand to pebbles or fragments of stone which, in some concretes, may be several inches in diameter. The aggregate occupies roughly three-quarters of the space within a given mass.

One of the important properties of aggregate for concrete is the gradation of the particles. In order to provide a dense packing or arrangement of particles in place, in a concrete mass, the aggregate must be suitably graded from fine to coarse.

A suitable gradation of the combined aggregate in a concrete mix is desirable in order to secure workability and to secure economy in the use of cement. For mixes of given consistency and cement content a well-graded mixture produces a stronger concrete than a harsh or poorly graded one. In general it has been found that a "continuous" grading including all size groups is the most satisfactory.

The U.S. Bureau of Reclamation specifications usually provide that the sieve analysis of a sand be within the following limits:

| Sieve Size | Percentage retained |
|------------|---------------------|
| No. 4      | 0-5                 |
| No. 8      | 5-15                |
| No. 16     | 10-25               |
| No. 30     | 10-30               |
| No. 50     | 15-35               |
| No. 100    | 12-20               |
| Pan        | 3-7                 |

Clay presence in the aggregate in the form of surface coatings interfere the bond between aggregate and the cement paste. Since good bond is essential to ensure a satisfactory strength and durability of concrete, the presence of clay is an unwanted problem [28, 29, 30].

In jet grout column formation the filler material which is called "aggregate" for concrete, is the in situ soil itself. As the aggregates in concrete mixes are graded from fine to coarse to produce stronger concrete, in order to achieve a composition and strength properties closer to the plain concrete, the grain size distribution of the in situ soil plays an important role in jet grouting technique. The fine aggregate used in concrete mix is sand with particles smaller than about 3/16 in diameter. As the sand content in the soil increases and the grain size distribution becomes similar to the given percentages in Table 8 the compressive strength of the jet grout columns increase. However as in the plain concrete presence of clay reduces the strength.

The compressive strength values for jet grout columns given in the literature and obtained from the case studies also show that for sandy and gravelly soils with relatively well-graded grain size distribution results in higher compressive strengths compared to the clayey soils.

Comparing the percentage of sand in the soil and obtained compressive strength values from the case studies a relationship is obtained and is given in figure 8. The amount of sand in the soil is obtained from the results of sieve analysis tests applied on specimens taken during borings. The term sand refers here to the soil which is obtained by extracting the soil retained on #4 sieve and extracting the soil with grain size passing #200 sieve. As the amount of sand in the in situ soil increase and the grain size distribution becomes well-graded, the compressive strength values of the jet grout columns also increase.
Table 8. Percentage of sand in the in situ soil in the case studies.

| Case Study | Percentage of sand in in-situ soil (%) | Compressive strength of jet grout columns (MPa) |
|------------|---------------------------------------|-----------------------------------------------|
| Site-1 – 1 | 37                                    | 2.0                                           |
| Site-1 -2  | 61                                    | 4.5                                           |
| Site-1 -3  | 21                                    | 1.6                                           |
| Site-2 - 1 | 52                                    | 3.0                                           |
| Site-2 – 2 | 58                                    | 4.6                                           |
| Site-3 - 1 | 41                                    | 2.8                                           |
| Site-3 - 2 | 49                                    | 3.3                                           |
| Site-3 – 3 | 53                                    | 2.8                                           |
| Site-4 - 1 | 67                                    | 5.0                                           |
| Site-4 - 2 | 47                                    | 3.9                                           |
| Site-4 – 3 | 59                                    | 4.9                                           |
| Site-5     | 56                                    | 4.8                                           |

Figure 8. Jet grout column strength versus amount of sand in the soil.

6. Effect of SPT blow counts on jet grout column strength

It was observed that the stiffness of the in situ soil which is mixed with water and cement under high pressure to form jet grout columns effects the strength properties of jet grout columns as well.

The average SPT blow counts for each case study up to jet grout column depths and the corresponding compressive strength values for jet grout columns are given in Table 9. The comparison between the SPT blow counts and the compressive strength of jet grout columns gives a linear relation which is given in Figure 9. Denser and/or stiffer soils in the site, results in higher compressive strength values of jet grout columns.
Table 9. Average SPT blow counts up to jet grout column depth.

| Case Study | Jet grout length (m) | Average SPT blow count | Average compressive strength of jet grout columns (MPa) |
|------------|----------------------|------------------------|------------------------------------------------------|
| Site-1     | 9                    | 7                      | 3.6                                                  |
| Site-2     | 8.5-9                | 12                     | 3.5                                                  |
| Site-3     | 7-14                 | 5                      | 3.0                                                  |
| Site-4     | 9-11.5               | 7                      | 3.8                                                  |
| Site-5     | 18                   | 20                     | 4.8                                                  |

Figure 9. Jet grout column strength versus SPT blow counts of the in situ soil.

7. Conclusions and recommendations
Jet grouting is considered as one of the main ground improvement technique since it offers the possibility of treating a wide range of soils from gravel to clay. This point is the main advantage of the jet grouting technique compared to other grouting techniques. The case studies also confirmed that by selecting the appropriate operating parameters and method, various types of soils are treated and predetermined diameters and strengths are obtained. Within the scope of the study the principal aspects of jet grouting technique and the strength properties of jet grout columns are discussed by referring to five case studies.

The physical properties of a jet grout column are the function of the in situ properties of the soil before treatment, the properties of the grout and the operational parameters of the jetting which are injection pressure, nozzle size, monitor rotation and withdrawal rates.

The strength of jet grout columns are assessed on the basis of compressive strength data which is measured by unconfined compression tests on samples obtained by coring.

The compressive strength characteristics are basically dependent on the nature and composition of the soil itself since the column is an in situ mixture of cement with water and soil. There are some major uncertainties in predicting Soilcrete composition and the strength. The in situ conditions may be very variable like it was also in the case studies provided above. The in situ water content of the soil may increase the water/cement ratio of the Soilcrete which results in a decrease in strength. Poor
control over jetting parameters such as variable jetting pressure, worn nozzles and lift rate and poor control over step size may have an adverse effect on strength. Insufficient mixing of soil and grout will cause the strength to be highest along the central axis and lower along the perimeter. Non-homogeneous soil with depth, groundwater chemistry and seepage velocities also effect the Soilcrete strength.

Regarding this much of variables, the jet grout column strength is not easy to predict and the design values have to be verified by proper testing procedure.

In order to study the strength properties of jet grout columns in various ground conditions five applications in Turkey are taken into consideration.

According to the results of case studies, comparing the percentage of sand in the soil and obtained compressive strength values, a linear relationship is obtained. As the amount of sand in the in situ soil increase and the grain size distribution becomes well-graded, the compressive strength values of the jet grout columns also increase in the case studies.

The stiffness of the in situ soil has also a significant effect on compressive strength of jet grout columns. The comparison of SPT blow counts and compressive strength values in the case studies shows that the increase in SPT blow counts increases the compressive strength of jet grout columns.

The compressive strength of jet grout columns are not easy to predict. There are many factors and conditions that effect the compressive strength of jet grout columns and it is not always easy to predict the final result. It is recommended that in every project quality and performance tests to be applied. The compressive strength values should be verified by applying unconfined compression tests on core samples.

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