

Impact of Jet-Grouting Pressure on the Strength and Deformation Characteristics of Sandy and Clayey Soils in the Compression Zone

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Abstract

Jet-grouting as a soil improvement method is extensively preferred in today's civil engineering practice. High-modulus grout columns constructed by extremely high jetting pressures displace the surrounding soil causing a densification in soil particles. Accordingly, the strength as well as the deformation characteristics of subsurface soils are relatively improved across the compression zone which is under the influence of high jetting pressure. In this study, the modification of soil properties in compression zone after jet-grouting in sandy and clayey soils is investigated by standard penetration tests (SPT) and multi-channel analysis of surface waves (MASW) performed at a couple of construction sites along established jet-grout column rows. The in-situ test results point out significant improvement of the measured parameters compared to initial values. The rate of enhancement in the compression zone is higher in sandy strata than that of clayey deposits. The strengthening of soil due to jetting pressure is validated by finite element analyses as well. Furthermore, very low shear strain values are obtained in clayey soils with respect to the improved characteristics of compression zone representing extremely low shear deformation under foundation.

Keywords: *Jet-grouting, soil improvement, soil-cement mixture column, compression zone, SPT, S-wave velocity*

1. Introduction

The improvement of foundation soils using various techniques is inevitable in weak soil layers. Though a variety of soil treatment methods are available in practice, jet-grouting and stone columns are a couple of commonly used stabilization techniques for ground improvement. Stone columns are constructed as vertical compacted aggregate columns by vibro-replacement while the jet-grouting is based on the high-pressure injection of water-cement grout through very small-diameter nozzles (Croce *et al.*, 2014). The injected grout treats the subsurface soil by forming a cylindrical soil and cement body. Jet-grouting has advantage over other stabilization methods and even injection techniques due to the fact that it can be applied in almost all soil types from clays to gravels irrespective of grain size distribution, void ratio or pore size (Fig. 1). High pressure jet-grouting (a minimum of 300 bar) radially cuts in-situ soil in order to mix and partially replace it with the grout (Croce *et al.*, 2014). The strength and deformation characteristics of the subsurface soil are improved after creating soil-cement mixture columns (Nikbakhtan and Ahangari, 2010; Bearce *et al.*, 2015).

Typically, high-modulus columns are strong enough to resist

vertical foundation and loads and earthquake forces. Furthermore, the subsurface soil properties among jet-grouting pattern is accepted to be constant before and after jet-grouting. Nonetheless, it is declared in various scientific studies that the jet-grouting pressures may be effective to a certain distance from the nozzle (Chepurnova, 2014).

A jet-grout column is erected through a 10 cm-diameter borehole which is drilled using the jet rods and a drill bit (Fig. 2). In addition, pre-cutting with high pressure water may be executed at the initial stages of drilling in dense, cohesive or very compact soils to enlarge the diameter of the jet-grout column (Lunardi, 1997). The rods and drill bit with jet-grouting nozzles are slowly lifted from the bottom by a rotating action. A homogenous cylindrical cement body is produced consisting of a mixture of injected grout and displaced soil after as the nozzles are kept rotating during jetting (Akin *et al.*, 2015a). The shape and dimension of the jet-grout column can be influenced by varying jetting pressure, lifting and rotation rate (Poh and Wong, 2001). Moreover, air and water besides cement during jet-grouting can also be used to execute larger diameter soil-cement mixture columns for specific soil types. Jet-grouting with solely cement grout (namely Jet-1 in practice) may be adequate for soft

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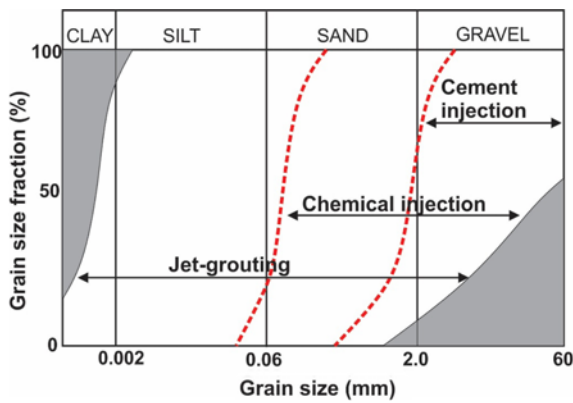


Fig. 1. Application Limits of Jet-Grouting for Various Soil Types (Modified after Passlick and Doerendahl, 2006)

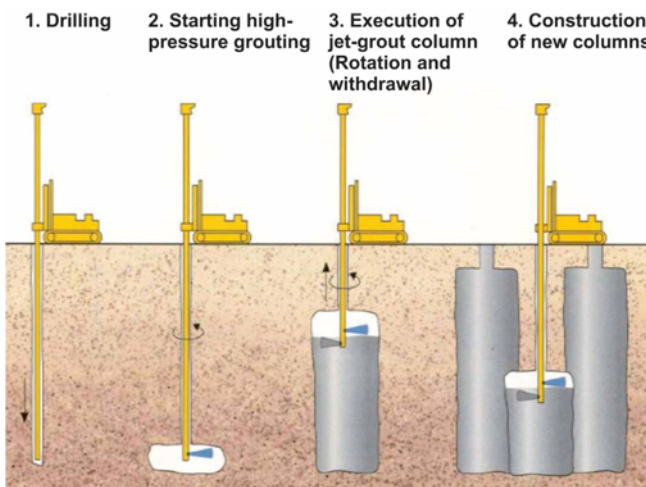


Fig. 2. Jet-Grouting Steps (Modified after Poh and Wong, 2001)

and loose soils, whereas the use of pressurized air besides grout (Jet-2) or pressurized air and water together with grout (Jet-3) should be preferred to achieve design column diameter in particularly stiff clays and dense sands (Croce *et al.*, 2014).

Jet-grout columns with specific spacing and diameter have significant impact on the mitigation of liquefaction since jet-grout columns and the surrounding in-situ soil jointly withstand the shear forces after an earthquake (Özsoy and Durgunoğlu, 2003; Madhav and Krishna, 2008). Furthermore, the bearing capacity and settlement properties of the foundation soils are confidently improved after jet-grouting applications (Greenwood, 1970; Wong and Poh, 2000; Sağlamer *et al.*, 2002; Bzówka, 2012; Juge, 2012; Juzwa and Bzówka, 2016).

Although several studies have been carried out to reveal the quality and the physico-mechanical properties (Fang *et al.*, 1994; Fang *et al.*, 2004; Gladkov *et al.*, 2011; Tinoco *et al.*, 2011; Akin, 2016) as well as to estimate the diameter of high-modulus columns (Flora *et al.*, 2013; Shen *et al.*, 2013; Ochmanski *et al.*, 2015), the interaction between extremely pressurized cement grout and the surrounding soil is rarely studied (Wang *et al.*, 2013; Wang *et al.*, 2014; Shen *et al.*, 2017). Nevertheless, it is reported in many studies that the high-pressure jetting triggers

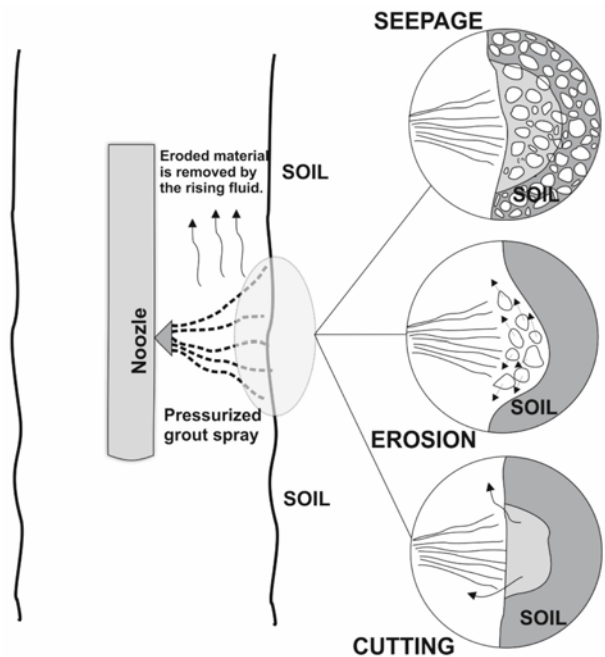


Fig. 3. Schematized View of Jet-Soil Interaction Mechanisms: Seepage, Erosion and Cutting (Modified after Croce *et al.*, 2014)

the deformation of nearby structures (Wong and Poh, 2000; Chepurnova, 2014). Similarly, high pressurized grout injected into the soil by horizontal jet-grouting can also induce the expansion of foundation soils causing significant uplift of the soils around jet-grouting locations (Wang *et al.*, 2016). The jet-grouting may exert substantial bending moments on the diaphragm walls which may lead to tilting as well (Wong and Poh, 2000). Deformation examples of neighboring structures caused by jet-grouting applications indicate that the injection of grout through jetting nozzles with extremely high pressure rates (~300 – 600 bar) forces the surrounding soil to displace laterally.

At the initial stages of jet-grouting, the nozzle and the soil to be treated is almost in contact. The erosion of particles on the drillhole wall occurs with the starting of jetting and is followed by the enlargement of grouted region. The construction of jet-grout column may occur as a result of three different jet-soil interaction mechanism depending upon the grain size of stabilized soil (Croce *et al.*, 2014). The erosion of particles is the dominant mechanism in coarse grained soils such as sands, gravels and sandy gravels. The seepage of grout through soil particles may also accompany to the formation of column. Contrary to coarse grained soils, the cutting of soil pellets can be observed in fine grained silty and clayey soils (Croce *et al.*, 2014) (Fig. 3).

After eroding the outer section of the soil, the injected grout keeps spreading in radial direction by shifting the soil grains and causing a displacement inside the soil mass. Thus, high pressure jetting forms a compressed soil zone among soil-cement mixture columns (Fig. 4). In engineering practice, the length of compression zone is commonly about 2 – 3 meters when the spacing of jet-grout columns in triangle or square array pattern is considered.

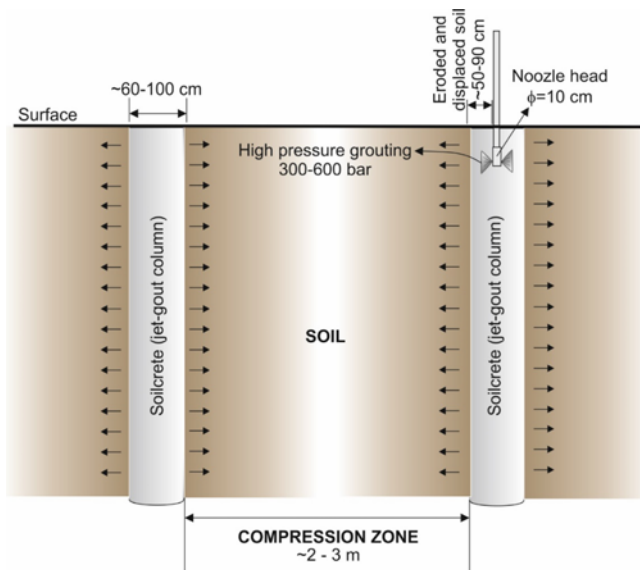


Fig. 4. Compressed Soil during High-Pressure Grouting between Jet-Grout Columns

The subsurface soil between columns is squeezed with a fluid pressure of 300 to 600 bars during jet-grouting. Accordingly, the density and eventually the strength of foundation soil are also improved as a result of increasing radial stress around jet-grout columns. It is obvious that the rate of compression gradually decreases with distance from soil-cement mixture columns, hence the degree of densification varies across the compression zone (Fig. 4).

The modification of density, stiffness and the strength of foundation soils after the installation of vibro-replacement stone columns is reported in several studies (Khrisna and Madhav, 2009; Bouassida *et al.*, 2013; Selçuk and Kayabali, 2015; Stuedlein *et al.*, 2015). The installation of stone columns by vibratory action increases the relative density of the adjacent soil as such granular piles are of displacement type. Although, higher amount of pressure towards the surrounding soil (300 – 600 bar) is applied at the time of jet-grouting application than that of vibratory stone column installation, researches investigating the improvement of either physical or mechanical properties of the adjacent soil after high-pressure grouting is very limited (Alkaya *et al.*, 2011).

The major aim of this research is to highlight the positive impact of jet-grouting pressures on the physico-mechanical parameters of surrounding soil among high-modulus columns. Consequently, a couple of construction sites at the eastern Turkey where the soils were improved by jet-grouting are evaluated. Hence, the impact of high-pressure jetting on the relative density and strength of the surrounding soil is investigated on the basis of field tests performed in sandy and clayey soils. The modification of the mechanical properties of the treated soil among soil-cement mixture columns is evaluated by standard penetration tests (SPT) as well as the multichannel analysis of surface waves (MASW) measurements. The data obtained are compared to the initial test

results to reveal the degree of improvement. Furthermore, the outcomes of this study are correlated with the previous studies performed by other researchers as well.

2. Description of Jet-Grouting Project Sites

2.1 Project Site-1

The first construction site is a waste water treatment plant located at the northern shore of the Lake Van (the largest lake of Turkey) in Erciş district (Fig. 5).

The Erciş district is located on a flat terrain where the elevation of the territory gently decreases towards the Lake Van. Fluvial and lacustrine deposits are widespread around the city settlement (Özvan *et al.*, 2008; Akin *et al.*, 2015b). Alluvial units are usually loose with moderate to low strength. Fluvial and delta deposits are commonly composed of gravelly and sandy clastics. Lacustrine deposits comprise commonly fine sand and silt as well as clay layers. The estimated depth of the alluvium is 190 m with respect to deep boreholes drilled for drinking/irrigation water projects.

A total of six geotechnical boreholes (SA-1 to SA-6) were drilled in order to investigate the subsurface layers and to determine the physico-mechanical properties of the foundation layers prior to jet-grout column application. In project site-1, well graded sand, silty sand and gravelly layers exist until 17 m from the surface following with a clayey unit at the bottom and the groundwater level is as shallow as 1 m. Besides drilling, seismic measurements using the MASW method were also carried out at three different alignments (S-1 to S-3). Having accomplished ground treatment, a couple of control boreholes (SJ-1 and SJ-2) were drilled among four jet-grout columns (at the center of four columns) to determine the variation of stiffness in sandy layers after jet-grouting (Fig. 5). It is important to note that the in-situ test results obtained after treatment are compared with the data of nearest borehole drilled at the preliminary site investigation (SJ-1 with SA-3, SJ-2 with SA-1). Similarly, four new MASW measurements (S-JG1 to S-JG4) were performed among jet-grout columns in parallel direction with the previous MASW surveys (S-1 and S-2). Finally, ground penetrating radar (GPR) was also employed at five locations just for the determination of jet-grout column length at the quality control stage of ground improvement studies.

Jet-grouting parameters such as jetting pressure, lifting and rotation rate play an important role on the formation of desired column width as well as on the efficiency of the treatment. Those parameters also affect the rate of compression of surrounding soil as the degree of compression increases with the jetting pressure and duration. The jet-grouting parameters applied during the installation of columns in project site-1 are summarized in Table 1. In accordance with the jet-grouting design, high-modulus columns constructed at the waste water treatment plant site using Jet-1 method (without water and air) are 0.6 m in diameter. A square array pattern with a spacing of 2.6 m (center to center) for an area replacement ratio of 11% was preferred at the project site-1 (Fig. 5). The maximum length of jet-grout

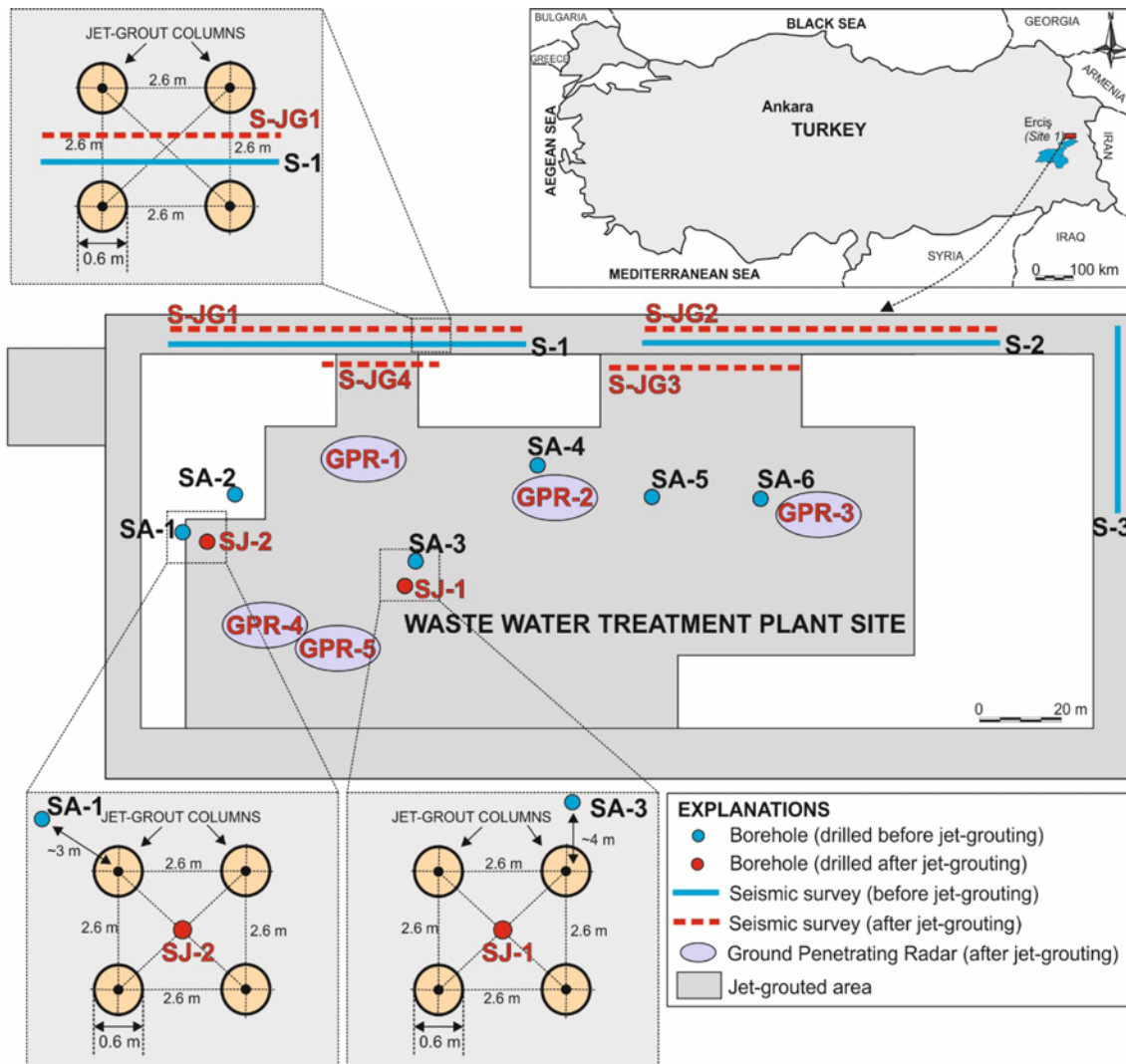


Fig. 5. The Location Map and Layout Plan of Project Site-1

Table 1. Several Jet-Grouting Parameters Applied at the Project Site-1

Parameter	Description
Jet-grouting method	Jet-1
Jet-pressure (bar)	450
Water/cement ratio	1/1
Maximum jet-grout length (m)	17
Jet-grout diameter (m)	0.6
Jet-grout spacing (m)	2.6
Area replacement ratio (%)*	11
Average lifting speed (cm/min)	50
Average rotation speed (rpm)	40

* $(\text{area of JG column in a unit cell} / \text{area of unit cell}) \times 100$

columns under foundation level is 17 m considering the liquefiable layers. The grout with a water/cement ratio of 1/1 was injected through nozzles using a jetting pressure of 450 bar. Finally, the average lifting and rotation speeds of nozzle head are 50 cm/min and 40 rpm, respectively (Table 1).

2.2 Project Site-2

The second soil stabilization site consists of high school and dormitory buildings located at the eastern border of Turkey in Yuksekova district (Fig. 6).

The district is settled on recent alluvial deposits of Quaternary age. The Quaternary deposits are comprised of loosely to moderately cemented gravel and sand as well as unconsolidated clay layers are observed within the region. The northern part of Yuksekova district is dominated by gravelly deposits and the southern part where the project site-2 is also located is characterized by clayey soils with shallow groundwater level (Akkaya *et al.*, 2013; Akkaya, 2015).

As the old school and dormitory buildings were in charge during the preliminary investigation phase, a number of 5 geotechnical boreholes (SA-1 to SA-5) were drilled around the perimeter of existing buildings before soil stabilization. Low plastic silty clay is the prevailing soil type for a depth of 15 m except a 1 m-thick silty sand layer considering the borehole and laboratory data. The groundwater level is around 1.5 – 2.0 m in

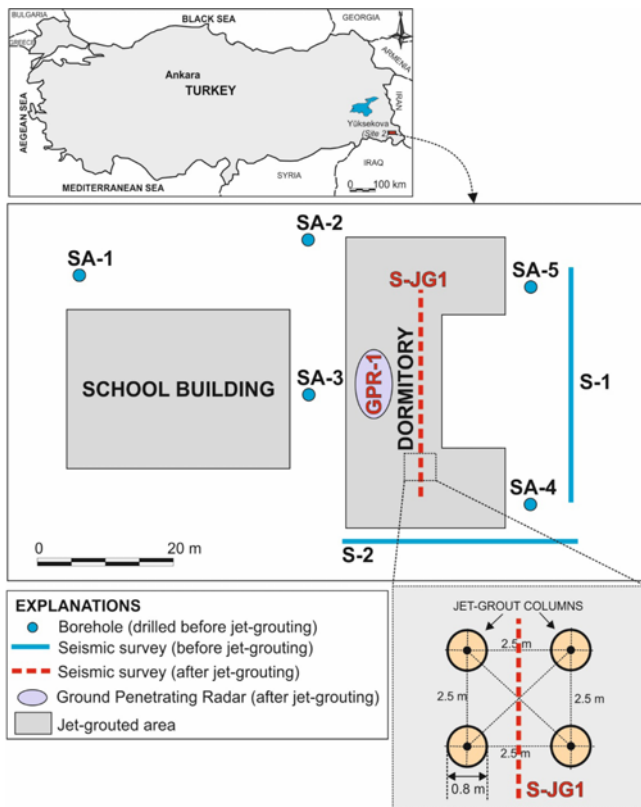


Fig. 6. The Location Map and Layout Plan of Project Site-2

Table 2. Several Jet-grouting Parameters Applied at the Project Site-2

Parameter	Description
Jet-grouting method	Jet-1
Jet-pressure (bar)	500
Water/cement ratio	1/1
Maximum jet-grout length (m)	13
Jet-grout diameter (m)	0.8
Jet-grout spacing (m)	2.5
Area replacement ratio (%)*	18.5
Average lifting speed (cm/min)	40
Average rotation speed (rpm)	35

*(area of JG column in a unit cell/area of unit cell) × 100

boreholes. The MASW surveys were executed at a couple of alignments (S-1 and S-2) nearby the dormitory building. After stabilizing the foundation soils by jet-grouting, a new MASW measurement (S-JG1) was performed between two jet-grout column rows in order to compare the S-wave velocities of stabilized soil with those of untreated one. Unfortunately, no boreholes were drilled after jet-grouting, so it is impossible to interpret the variation of SPT-N blows of the surrounding soil after the installation of jet-grout columns. Ground penetrating radar (GPR) was employed at one location for the determination of jet-grout column length at the quality control stage.

The jet-grouting parameters of the project site-2 are summarized in Table 2. Jet-grout columns in 0.8 m diameter were installed at

project site-2 in clayey soil layers with a square pattern (Fig. 6). The area replacement ratio of columns with a 2.5 m spacing is around 18.5%. Slightly higher jetting pressure (500 bar) than that of the project site-1 was applied at the project site-2 to form the columns in silty clay deposits. On the contrary, the lifting and rotation speeds of nozzles were selected to be lower to construct relatively larger columns in low plastic clayey units. The improved soil depth is approximately 13 m from the surface level.

3. Effect of Jet-Grouting on the SPT-N Blow Counts of the Surrounding Soil

The adjacent soil around jet-grout columns is eroded and excessively displaced due to high-pressure jetting during jet-grouting operations. Accordingly, the soil particles are forced to relocate causing a decrease in pore size. The reduction in pore size results in gradual improvement of adjacent soil properties. The enhancement of strength and density properties of the surrounding soil after jet-grouting is evaluated on the basis of the Standard Penetration Test (SPT) results for the project site-1. A couple of 20 m-deep boreholes (SJ-1 and SJ-2) were drilled among four jet-grout columns at the project site-1 in order to detect the variation of SPT-N blow counts of the surrounding soil after high pressure jetting (Fig. 5). The results are compared with the SPT blow counts of the nearest boreholes (SA-1 and SA-3) drilled before ground improvement for the preliminary investigation purposes.

The variation of fines content and water content of subsurface soil in pre-drilling and post-drilling boreholes is presented in Fig. 7. The fines content of the foundation soils at the project site-1 is commonly lower than 10% until 10 m depth except a few layers. A gradual increase in fines content is noticeable after 10 m and the soil contains more than 50% fines below 17 m (Fig. 7(a)). The sieve analysis data of four boreholes are commonly compatible with each other indicating that the boreholes are drilled in similar soil profiles and thus the impact of jet-grouting can be relatively compared. Furthermore, the water content of soils in the jet-grouted zone of post-drilling boreholes is slightly lower than the water content of soils in preliminary boreholes (Fig. 7(b)). The decline of water content of soils among jet-grout columns can be attributed to the decrease of pore size on account of high jetting pressures since preliminary site investigations and drilling after jet-grouting were carried out in the same season within one-year time interval.

The performance of soil treatment is evaluated based on the improved physico-mechanical properties of soils such as void ratio, density, deformation modulus etc. (Khrisna and Madhav, 2009). The modification of those parameters are commonly estimated in-situ via Cone Penetration or Standard Penetration Tests. The Standard Penetration Tests performed particularly among stone or jet-grout columns are used to measure the efficiency of soil stabilization in various studies (Khrisna and Madhav, 2009; Akkaya *et al.*, 2011). In this study, the densification of stabilized sandy soil after jet-grouting operations at the project

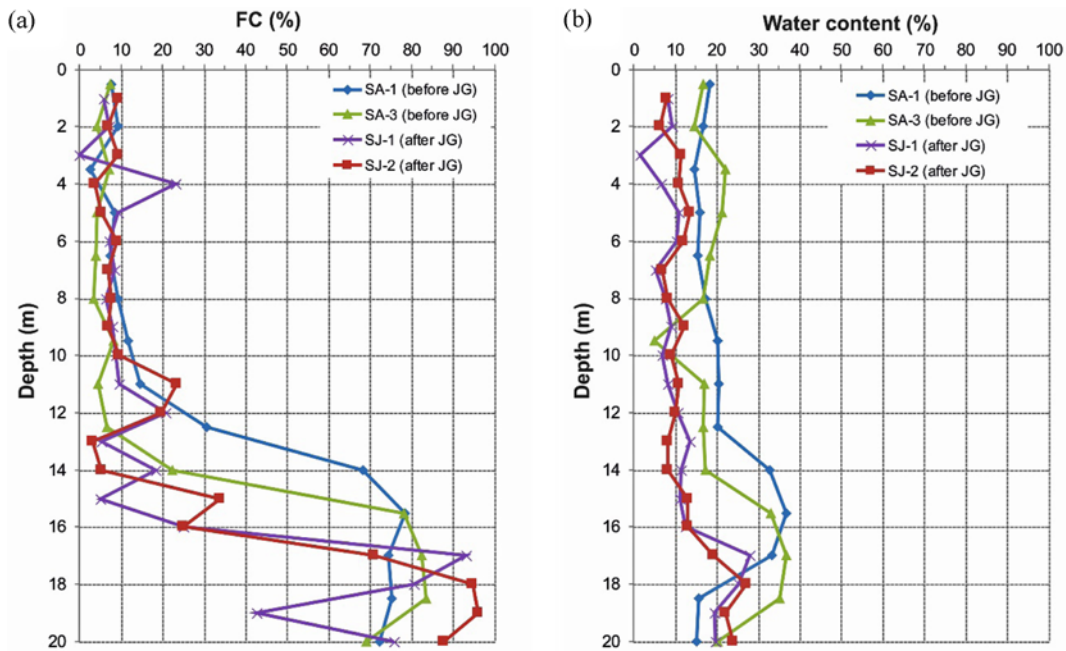


Fig. 7. Soils in Pre-drilling and Post-drilling Boreholes at the Project Site-1: (a) The Variation of Fines, (b) Water Content

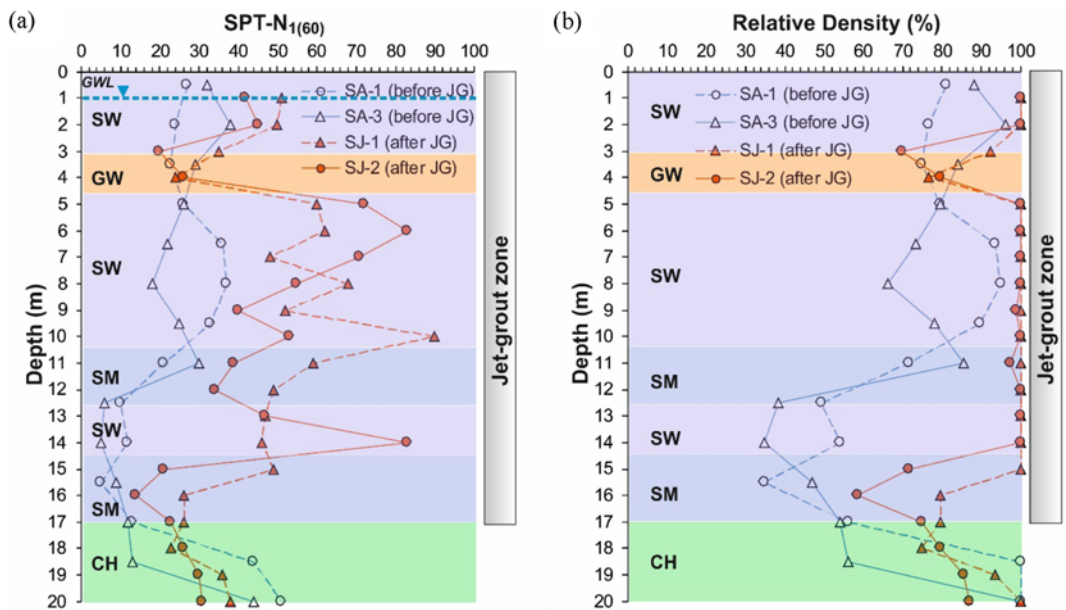


Fig. 8. Pre- and Post-Drilling Boreholes at the Project Site-1: (a) The Variation of SPT-N₁₍₆₀₎, (b) Relative Density

site-1 is assessed considering the SPT-N₁₍₆₀₎ values. The variation of SPT-N₁₍₆₀₎ values as well as the relative density through depth for an area replacement ratio of 11% is depicted on a generalized soil profile in Fig. 8. The area replacement ratio (a_s) is defined by the equation below.

$$a_s = (a/b)^2 \times 100 \quad (1)$$

where a and b are the radii of the jet-grout column and of the unit cell (length of an imaginary touching square surrounding four columns in a square array), respectively.

A considerable increase for the SPT-N₁₍₆₀₎ values of medium dense-dense sandy soils is remarkable in the boreholes drilled

along the jet-grout compression zone except the gravelly layer (gravel-sand mixtures) between 3.0 and 4.5 m depth indicating that the gravel particles were not significantly affected by high-jetting pressures. Similarly, no progressive variation is observed in the clay unit after 17 m since the layer is below the jet-grout treatment zone (Fig. 8(a)). The densification of sandy soils after jet-grout treatment is apparent with respect to N₁₍₆₀₎ values. Thus, the relative density of compressed soil is also increased as high as 100% after a maximum of 450 bar jetting pressure (Fig. 8(b)).

A similar study performed by Alkaya *et al.* (2011) point out that a considerable improvement of the surrounding soil can be achieved after jet-grouting in accordance with the field studies at

two different project sites. In that study, the average SPT-N blow counts of the unimproved soil at the project sites are reported as 5 and 11, respectively. The SPT-N values attain maximum values of 38 and >50 after jet-grouting although no detailed information about the location of in-situ test boreholes, jetting pressures and the soil types is presented.

The statistical relationship between $SPT-N_{1(60)}$ -treated and $SPT-N_{1(60)}$ -untreated values for various depths of sandy deposits is depicted in Fig. 9. It should be noted that the correlation is valid for an area replacement ratio of 11%. A moderately

significant relationship (correlation coefficient, $r = 0.69$) is noticeable between the modified $SPT-N_{1(60)}$ value of the treated soil and the $SPT-N_{1(60)}$ values before soil stabilization. The correlation can be expressed as follows.

$$SPT-N_{1(60)} - treated = 9.1 \times (SPT-N_{1(60)} - untreated)^{0.55} \quad (r = 0.69) \quad (2)$$

4. Effect of Jet-Grouting on the S-Wave Velocity of the Surrounding Soil

The properties of soil materials (e.g., elasticity modulus, shear modulus, bulk modulus, seismic amplification, Poisson's ratio) are closely related to the shear wave (S) velocity. Therefore, the determination of S-wave velocity of subsurface layers is important in geotechnical engineering. Recently, Multi-channel Analysis of Surface Waves (MASW) method has been widely used to determine near surface S-wave velocity. The MASW method was introduced by Park *et al.* (1999). In general, MASW surveys can be divided into active and passive surveys based on how the surface waves required for analysis are acquired. The MASW method can be divided into three main steps; data acquisition, dispersion analysis and inversion analysis (Park *et al.*, 1999). Data acquisition configuration resembles a conventional seismic refraction survey. However, MASW field parameters (e.g., source power, sampling interval, record length) are more flexible than seismic refraction or reflection surveys (Dikmen *et al.*, 2010). The most important advantage of the method is the fast data acquisition, easy data-processing and overcoming a low-velocity layer problem. In the last decade, a number of both theoretical and experimental studies have been made on the method.

MASW surveys were carried out at the investigated construction

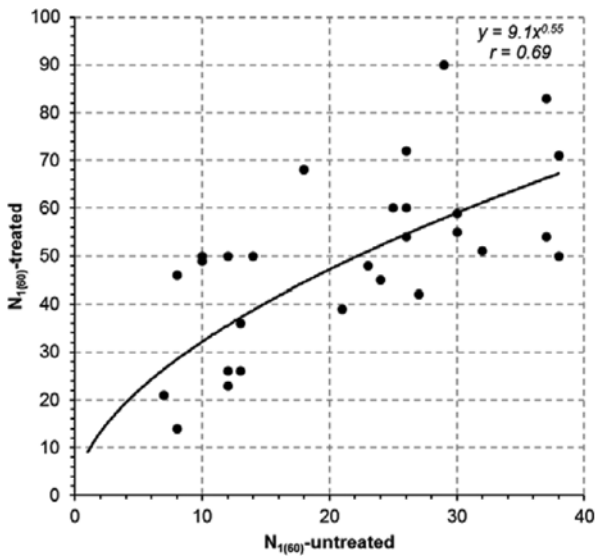


Fig. 9. Statistical Relationship between $SPT-N_{1(60)}$ -treated and $SPT-N_{1(60)}$ -Untreated Values Gathered at the Project Site-1 from Various Depths

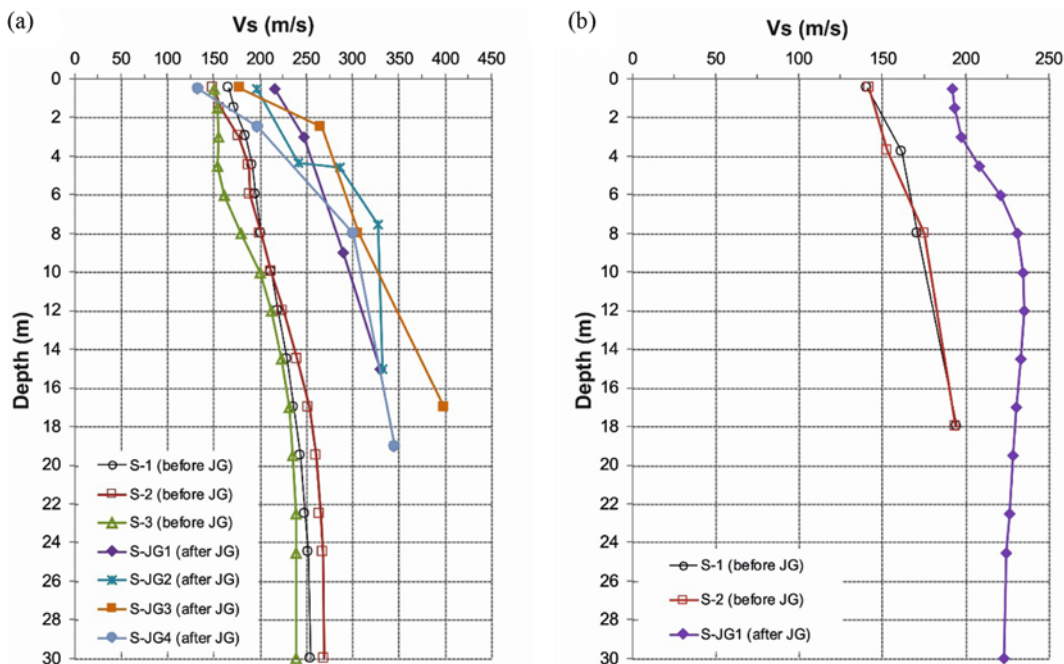


Fig. 10. The Variation of Shear Wave Velocity with Depth before and after Jet-Grouting: (a) At the Project Site-1, (b) At the Project Site-2

sites to highlight the variation of S-wave velocity after jet-grouting improvement. As aforementioned, the subsurface layers of the project site-1 are dominated by sandy deposits whereas a thick clayey unit exists at the second ground improvement site. The variation of shear wave velocity of subsurface layers with depth for both project sites is illustrated in Fig. 10.

The seismic exploration depth is 30 m at the preliminary investigation phase of the project. The untreated sandy layers at the project site-1 expose shear wave velocities between 150 and 250 m/s (Fig. 10(a)). A gradual increment up to 250 m/s is remarkable until 16 m and the rate of shear wave velocity is almost constant after this depth. The shear wave velocities of surrounding soils in the compression zone substantially escalate as a result of high pressure grouting considering the seismic surveys which was repeated between jet-grout columns. Nevertheless, the seismic survey depth was restricted to 18 m bearing in mind the length of columns. The shear wave velocity of treated sandy soil at the project site-1 is commonly over 300 m/s after 8 m (Fig. 10(a)). Furthermore, a maximum shear wave velocity value of 390 m/s was also obtained in one of the seismic survey lines that is almost 60% higher than the velocity of unimproved soil at the same depth.

The SPT-N values of low plasticity clay layers at the project site-2 vary between 5 and 15 signifying moderately stiff – stiff clay deposits (Fig. 11). However, the shear wave velocities of these layers are very low and range between 150 and 190 m/s (Fig. 10(b)). Although the seismic investigation depth is around 18 m at the project site-2, the soil profile of the site can be classified as E type ($V_s < 180$ m/s) in accordance with the NEHRP Soil Profile Type Classifications (Building Seismic

Safety Council, 2003). After jet-grout treatment, the shear wave velocity of the subsurface clayey soil between jet-grout columns increases as high as 240 m/s at around 10 – 12 m and no significant rise can be observed after the jet-grout zone improvement zone (>13 m) (Fig. 10(b)). The improvement rate in clayey soil is approximately 37% with respect to maximum shear wave velocity increment which is reasonably lower than in sandy soils (60%) at the project site-1. It is quite logical since the construction of high-modulus columns in desired dimensions in stiff clayey soils is also harder than in sandy deposits. In other words, the jetting pressure is less effective on the compression zone of stiff clayey soils than sands considering the fact that higher jetting pressures were applied in the second project site consisting of clayey deposits.

Similarly, an increase in soil seismic parameters after jet-grouting is also mentioned in the study of Alkaya *et al.* (2011). The initial shear wave velocities of compression zones at two different sites, which are reported to be 90 m/s and 113 m/s, are amplified to 210 and 341 m/s after jet-grout stabilization. Despite the unknown soil type and jetting pressures, the increment rate of seismic parameters in Alkaya *et al.* (2011) seems to be higher than the one in this study.

5. Improved Bearing Capacity of Jet-Grout Columns

Although there is no common calculation method for the bearing capacity of jet-grout columns, the most favorable assumption is considering the jet-grout column as an isolated structural member and calculating the bearing capacity similar to the reinforced concrete piles (Bzowka, 2014). Thus, one of the advantageous points of the modified surrounding soil characteristics as a result of jet-grouting pressure is the improved bearing capacity of jet-grout piles since the skin friction between high-modulus columns and the surrounding soil is higher than expected.

For a pile with a structural strength to carry a certain loading, the total downward capacity (Q_{total}) of the pile is controlled by the properties of the soil surrounding and underlying the column (McCarthy, 2007). The ultimate bearing capacity of a concrete pile is the sum of skin resistance developed along the surface of the pile (Q_{skin}) as well as the end bearing at the tip of the pile (Q_{tip}).

$$Q_{total} = Q_{skin} + Q_{tip} \tag{3}$$

To show the interaction between the jet-grout column and the surrounding soil, the total bearing capacity of a single jet-grout column is calculated for two different cases. For the first case the bearing capacity of the jet-grout pile constructed at the project site-1 (coarse grained soil) is determined considering the initial properties of the surrounding soil. On the other hand, improved soil characteristics due to jet-grouting pressures is taken into consideration for the second case.

In the first case scenario, the ultimate bearing capacity of a single jet-grout column with 0.6 m diameter and 17 m depth

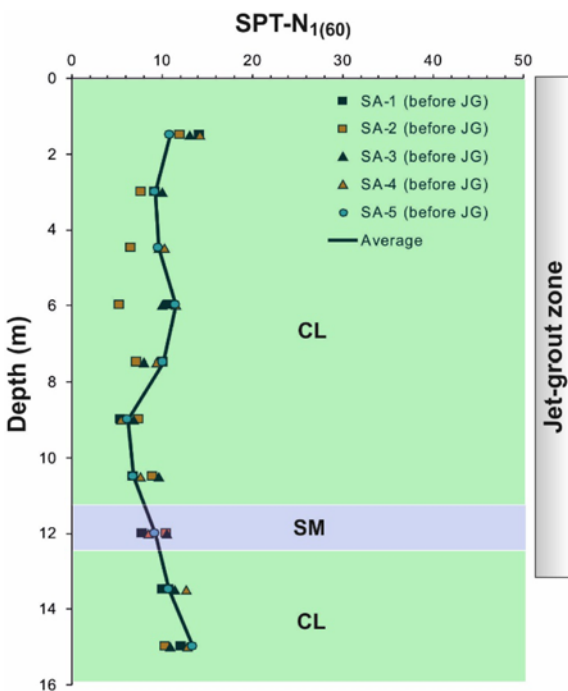


Fig. 11. The Variation of SPT-N₁₍₆₀₎ in Preliminary Investigation Boreholes (before Jet-Grouting) at the Project Site-2

(project site-1) is calculated as 96 tons. The skin friction resistance is determined to be 1.55 ton/m² during the calculations. Furthermore, the ultimate bearing capacity of the jet-grout column escalates as high as 238 tons with a skin friction resistance of 2.37 ton/m² when the parameters of stabilized surrounding soil after jet-grouting pressures is accepted for the second case.

The bearing capacity calculations of jet-grout piles point out that the compression zone around jet-grout columns with improved physico-mechanical soil properties has a significant impact on the bearing capacity of columns due to high skin friction resistance between the jet-grout pile and soil.

6. Estimation of the Deformation Parameters of Uncompressed and Compressed Soils

The deformation parameters of uncompressed (before jet-grouting) and compressed soils (after jet-grouting) such as elasticity modulus (E_m), shear modulus (G), bulk modulus (K) and Poisson's ratio (ν) are determined on the basis of seismic velocities (V_p and V_s) of a couple of layers at the project sites. Accordingly, the elasticity and bulk moduli and the Poisson's ratio of soil layers are calculated using the equations proposed by Bowles (1988) as well as the shear modulus is defined by the formula in Kramer (1996), which are depicted below.

$$G = (\gamma * V_s^2) / 100 \text{ (kg/cm}^2\text{)} \quad (4)$$

$$E_m = 2.G.(1 + \nu) \text{ (kg/cm}^2\text{)} \quad (5)$$

$$K = (E_m / 3.(1 - 2\nu)) \text{ (kg/cm}^2\text{)} \quad (6)$$

$$\nu = (V_p^2 - 2.V_s^2) / (2.V_p^2 - 2.V_s^2) \quad (7)$$

The initial deformation parameters of sandy soils at the project site-1 are summarized together with the results of compressed soil in Table 3. A significant amplification in deformation parameters is obvious considering the increment in seismic velocities. It is noteworthy to mention that the initial unit weight of foundation sandy soil is around 14 kN/m³ (medium dense) and is improved to a value of 16 kN/m³ after jet-grouting. The subsurface layers chiefly consisting of sand are accepted to be weak with respect to the elasticity modulus. After jet-grouting, the elasticity modulus of the improved sand in the compression

Table 3. Deformation Parameters of Uncompressed and Compressed Sandy Soil at the Project Site-1

Layer	Depth (m)	V_p (m/s)	V_s (m/s)	E_m (MPa)	G (MPa)	K (MPa)	ν
Before JG improvement (uncompressed)							
1	0 – 5	746	216	215	74	784	0.45
2	5 –	1,049	296	441	151	1,699	0.46
After JG improvement (compressed)							
1	0 – 5	808	293	396	139	871	0.42
2	5 –	1,186	348	627	216	2,218	0.45

V_p = P-wave velocity, V_s = S-wave velocity, E_m = Elasticity modulus (Bowles, 1988), G = Shear modulus (Kramer, 1996), K = Bulk modulus (Bowles, 1988), ν = Poisson's ratio (Bowles, 1988)

Table 4. Deformation Parameters of Uncompressed and Compressed Clayey Soil at the Project Site-2

Layer	Depth (m)	V_p (m/s)	V_s (m/s)	E_m (MPa)	G (MPa)	K (MPa)	ν
Before JG improvement (uncompressed)							
1	0 – 3.7	440	153	93	33	249	0.43
2	3.7 –	520	194	155	55	311	0.42
After JG improvement (compressed)							
1	0 – 3.7	380	192	131	49	128	0.33
2	3.7 –	1,120	238	294	99	2,070	0.48

V_p = P-wave velocity, V_s = S-wave velocity, E_m = Elasticity modulus (Bowles, 1988), G = Shear modulus (Kramer, 1996), K = Bulk modulus (Bowles, 1988), ν = Poisson's ratio (Bowles, 1988)

zone of jet-grout columns is between 400 and 600 MPa indicating moderate strength. A similar outcome can be derived considering the rates of bulk and shear moduli of compressed sand. It can be concluded that the deformation characteristics of compressed sandy soils are significantly modified by high jetting pressures.

The deformation parameters of clayey soils at the project site-2 are listed in Table 4. The compressed clayey soil reveals a maximum elasticity modulus of approximately 300 MPa. Despite 50% increase in elasticity modulus after compression, the compressed clay unit can still be classified as weak soil. Moreover, the deformation characteristics of compressed clayey soil are tremendously lower than those of sandy units at the first improvement site.

7. Evaluation of the Effect of Jet-Grouting Pressure on the Deformation Characteristics of Foundation Soils by Finite Element Analyses

In engineering practice, the bearing capacity and settlement characteristics of jet-grout columns are assessed similar to reinforced concrete piles. The end (tip) and side-frictional bearing capacity of jet-grout columns are calculated following the same methodology applied for driven piles though the external surface of a jet-grout column is much more irregular than relatively smooth concrete pile. Aside from those, the improvement of the physico-mechanical properties of surrounding soil in the so-called compression zone of jet-grout columns is always neglected. Nonetheless, as determined in this research, the foundation soil in the compression zone is modified after high jetting pressures during the construction of columns.

Consequently, possible effect of modified soil characteristics of the compression zone on the stresses and displacements in foundation soils is evaluated for sandy and clayey deposits via finite element analyses using the RS2 v.9.0 software (Rocscience Inc., 2017). The subsurface soil profile in the finite element analyses are constructed on the basis of MASW measurements. Accordingly, deformation parameters of two layers in the models are derived from the same seismic surveys carried out at the project sites. The model boundaries in finite element analyses are set far enough from the edge of the improved zone not to affect the deformation characteristics of the subsurface soil. A maximum

Table 5. Deformation and Shear Strength Parameters of Subsurface Sandy Soils and Jet-GROUT Columns at the Project Site-1 Employed in Numerical Analyses

	Layer	E_m (MPa)	ν	c (kPa)	ϕ ($^\circ$)	γ (kN/m ³)
Original (Before Jet-Grouting)	Layer-1 (0 – 5 m)	215	0.45	8	15	15
	Layer-2 (5 – 40 m)	441	0.46	7	23	16
Improved (After Jet-Grouting)	Layer-1 (0 – 5 m)	396	0.42	7	23	16
	Layer-2 (5 – 40 m)	627	0.45	7	35	17
	Soilcrete (17 m)	10,417	0.40	10	45	25

E_m = Elasticity modulus, ν = Poisson’s ratio, c = Cohesion, f = Internal friction angle, γ = Unit weight

Table 6. Deformation and Shear Strength Parameters of Subsurface Clayey Soils and Jet-GROUT Columns at the Project Site-2 Employed in Numerical Analyses

	Layer	E_m (MPa)	ν	c (kPa)	ϕ ($^\circ$)	γ (kN/m ³)
Original (Before Jet- Grouting)	Layer-1 (0 – 3.7 m)	93	0.43	20	3	17
	Layer-2 (3.7 – 40 m)	155	0.42	26	5	18
Improved (After Jet-Grouting)	Layer-1 (0 – 3.7 m)	131	0.33	25	5	17.5
	Layer-2 (3.7 – 40 m)	294	0.48	30	6	18.5
	Soilcrete (13 m)	10,333	0.40	15	40	25

E_m = Elasticity modulus, ν = Poisson’s ratio, c = Cohesion, f = Internal friction angle, γ = Unit weight

of 100 kPa foundation pressure is accepted for both sites. The original (before jet-grouting) and improved (after jet-grouting) shear strength and deformation parameters used in finite element analyses are summarized in Tables 5 and 6.

A couple of cases are modelled in numerical analyses considering the parameters presented in Tables 5 and 6. In the first case, no improvement of adjacent soil among jet-grout columns is considered. Hence, the original soil parameters determined during the preliminary investigation phase (before jet-grouting) are assigned to the foundation soils. Controversially, a compression zone with enhanced soil characteristics is modelled around jet-grout columns in the second case. Thus, the parameters obtained after jet-grout column construction are accepted for the compression zone in finite element analyses.

The rate of total displacement and maximum shear strain determined by numerical analyses for the investigated project sites are presented in Figs. 12 and 13, respectively. As seen in Figs. 12(a) and 12(c), the improvement of the sandy soil characteristics in the compression zone at the project site-1 has no significant effect on the degree of total displacement. The maximum total displacement after jet-grout construction is 3 mm when the compression zone is neglected. Furthermore, a maximum of 2 mm total displacement is calculated by numerical analysis despite the improved characteristics of the compression zone. A similar result is obtained for the clayey soils at the project site-2 (Figs. 13(a) and 12(c)). Although the rate of total displacement in clayey deposits of project site-2 is higher (around 9 mm) than in sandy soils of project site-1, no considerable variation of total displacement can be reported for two different cases. The numerical analyses point out that the modified soil characteristics of the compression zone among jet-grout columns do not significantly contribute to resist the foundation pressures since high-modulus columns reveal substantially higher elasticity modulus than the adjacent soil and the columns act similar to reinforced concrete

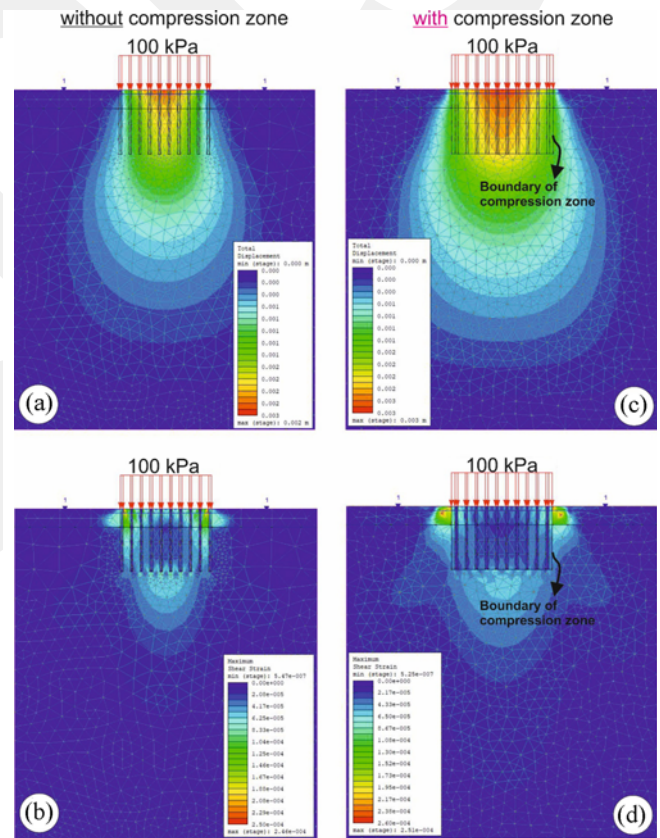


Fig. 12. Two Different Cases at the Project Site-1: (a) Total Displacement without Compression Zone, (b) Maximum Shear Strain without Compression Zone, (c) Total Displacement with Compression Zone, (d) Maximum Shear Strain with Compression Zone

piles by transferring the vertical loads across their full heights by side friction as also stated by Müller (2004) and Juzwa and Bzowka (2016). In other words, the jet-grout piles dominantly

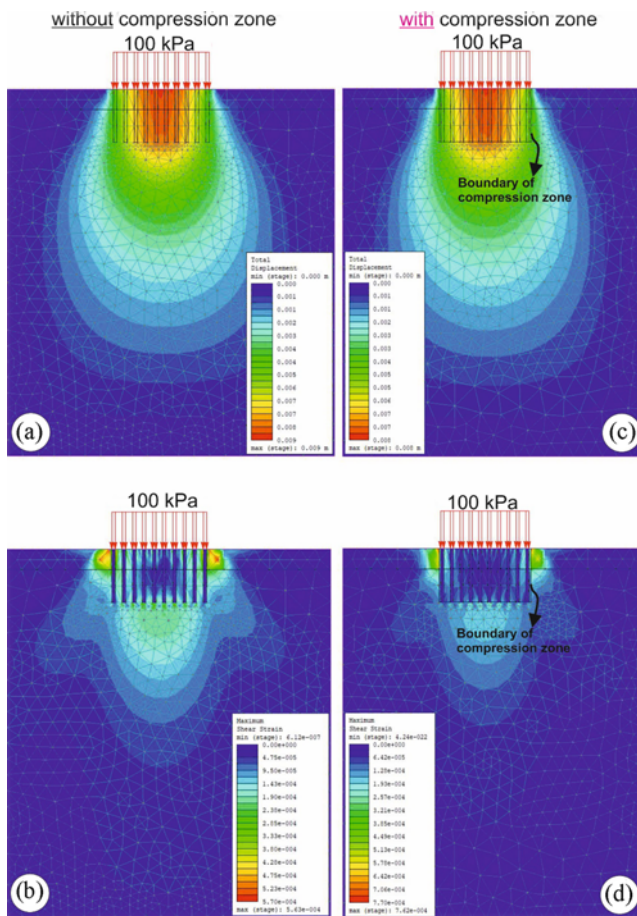


Fig. 13. Two Different Cases at the Project Site-2: (a) Total Displacement without Compression Zone, (b) Maximum Shear Strain without Compression Zone, (c) Total Displacement with Compression Zone, (d) Maximum Shear Strain with Compression Zone

resist the foundation pressures without conveying the loads to the adjacent soils due to the fact that a substantial strength variance exist between the columns and the soil.

Strain is a measure of material deformation and a non-dimensional parameter. When the shear stresses act along a surface, the material is forced to distort in parallel with the surface. The rate of maximum shear strain (under 0.3 g seismic load) in sandy and clayey soils of this study is also evaluated via numerical analyses. The maximum shear strain in sandy deposits is 0.000246 while the maximum shear strain attains a value of 0.000251 when a compression zone around jet-grout columns is considered (Figs. 12(b) and 12(d)). Although the maximum shear strain around the jet-grout columns remains constant for both cases, an increase in the maximum shear strain outside the compression zone is remarkable (Fig. 12(d)). Correspondingly, a noteworthy variation of the maximum shear strain is not obvious in clayey soils (Figs. 13(b) and 13(d)). The rate of maximum shear strain attains a minimum value of 0.000563 among columns in clayey soils. As seen in the results of finite element analyses (Figs. 12(b), 12(d), 13(b) and 13(d)), the maximum shear strain is

concentrated at the outer sections of jet-grout columns.

8. Conclusions

Jet-grout or so-called high-modulus columns constructed to resist vertical structural loads under foundations as well as seismic loads are designed considering a number of assumptions. One of the most advantageous points of jet-grouting is the high jetting pressure during grout injection. The improved subsurface soil is ripped by excessively pressurized grouting to erect the column in desired dimensions. The surrounding soil around jet-grout columns is also forced to displace laterally to some extent under high jetting pressures resulting in reduction of pore volume and thus improved soil characteristics. In this study, the rate of improvement in adjacent soil as a result of jet-grouting pressure is investigated via in-situ surveys at a couple of locations with different soil profiles. The Standard Penetration Tests as well as MASW surveys performed among jet-grout columns, or in other words in the compression zone, signify considerable increase for the measured parameters after jet-grouting pressures. Loose sandy soils are found to be more sensitive to jetting pressures compared to stiff clay deposits taking the in-situ test results into account. Moreover, with respect to finite element analyses, the escalation of relative density and stiffness of soils in the compression zone as a result of high pressure jetting do not significantly affect the rate of total displacements since high-modulus jet-grout columns dominantly withstand the foundation loads by side friction and end-bearing. However, the strength of soil in the compression zone, specifically in sandy deposits, is remarkably increased through excessive jetting pressures.

Though high-modulus columns are very rigid and dominantly counteract foundation pressures on their own, considering a compression zone among those high-modulus columns may not only help jet-grouting design but also the assessment of liquefaction and bearing capacity. Moreover, it is quite obvious that the side friction between jet-grout column and the surrounding soil is enhanced as a result of improved characteristics of surrounding soil. Therefore, the bearing capacity of jet-grout column should be higher than expected. One of the most important features of jet-grouting affecting the soil improvement cost is the spacing of jet-grout columns. The existence of a compression zone formed by pressurized grouting in jet-grouting applications is neglected during the determination of jet-grout column spacing. Therefore, researches revealing the influence of a compression zone on column spacing should be carried out with detailed in-situ surveys executed on different soil types.

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Notations

a = Radii of jet-grout column

a_s = Area replacement ratio

b = Radii of unit cell

E_m = Elasticity modulus

G = Shear modulus

K = Bulk modulus

Q_{skin} = Skin resistance developed along the surface of pile

Q_{tip} = End bearing capacity of pile

Q_{total} = Total bearing capacity of pile

r = Correlation coefficient

$SPT-N_{1(60)-treated}$ = Corrected SPT-N blow count after jet-grouting

$SPT-N_{1(60)-untreated}$ = Corrected SPT-N blow count before jet-grouting

V_p = P-wave velocity

V_s = S-wave velocity

γ = Unit weight

ν = Poisson's ratio

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