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The Effect of Pulling and Rotation Speed on the Jet Grout Columns

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Abstract**—**The performance of jet grout columns was affected by many controlled and uncontrolled parameters. The leading parameters for the controlled ones can be listed as injection pressure, rod pulling speed, rod rotation speed, number of nozzles, nozzle diameter and Water/Cement ratio. And the uncontrolled parameters are soil type, soil structure, soil layering condition, underground water level, the changes in strength parameters and the rheologic properties of cement in time. In this study, the performance of jet grout columns and the effects of pulling speed and rotation speed were investigated experimentally. For this purpose, a laboratory type jet grouting system was designed for the experiments. Through this system, jet grout columns were produced in three different conditions. The results of the study showed that the grout pressure and the lifting speed significantly affect the performance of the jet grouting columns.

Keywords**—**Jet grout, sandy soils, soil improvement, soilcrete.

I. Introduction

IMPROVING the characteristics of soil by using "jet grouting" has been commonly applied in recent years. As a result of applying this technique, the bearing capacity of soil increases, the settlements and permeability decrease, and the soil resistance against liquefaction also increases. The significant advantages of this method can be listed as; its ability of being applicable for different geotechnical engineering applications of various soil conditions, its economic side in comparison to other alternative methods and its production process completed in a short period of time.

The method consists of drilling, cutting and washing processes performed on soil by using horizontal and vertical water jets. During the processes, a special driller was used which allows soil to merge with the injection by the help of the horizontal jetting nozzles with high pressure during the withdrawal of the drill. And in this way, it creates high modulus and dense columns. Jet grouting technique can be applied in three different ways in terms of its drilling and production processes. [1]

In a single-fluid system (Jet-1), the injection material (grout) is sent through a specially-designed rod formed with holes of particular diameter (nozzle) to the soil under high pressure (400-500 bars). During this process, the rod is pulled up by rotating with a constant speed. The cement-soil mixture that was mixed under high pressure gets hardened in the course of time. In this way, the cylindrical columns (soilcrete) of specific length and diameter are formed inside the soil which are more rigid in comparison to soil and produced within the soil. [1] In double-fluid system (Jet-2), the combination of grout and compressed air is injected together with high pressure to provide the mixture of more amount of soil with grout. In triple-fluid system (Jet-3), the injected three fluids are grout, air and water to obtain the best amount of soil-grout mixture. Although the single and double-fluid systems can be mostly used for loose sandy soils, the three-fluid system can be used in all types of soils. [1]

The characteristics and performance of the column formed by jet grout method depend not only on the production method but also on the different application parameters. In order to determine the effects of these parameters on the performance of JG columns, carrying out a parametric in-situ test is quite difficult in terms of time and cost. Therefore, in order to make tests in the laboratory, JG columns are produced in the laboratory using a specially designed laboratory type JG column device. [1]

In this study, the effects of the parameters on the formation of the columns were studied by introducing the specially designed laboratory device to determine the effects of the design factors on the performance of the jet grout columns.

II. Previous Studies

A few of the studies in technical books and articles about the design and application stages of "jet grout columns" are given in the following briefly.

Omine et al. suggested a homogenization method called as two-phased mixture method to evaluate the stress/deformation relationship of the mixtures made of different elastic materials. The stress distribution factor was calculated using Eshelby Tensor. The yield stress and the average modulus of elasticity of composite soils were obtained using this homogenization method which is mostly applied on the soils improved by stone columns with cement additives. The stress/deformation relationship, the average modulus of elasticity and the yield stress of the mixtures were also developed from the suggested model. For the reliability of the method, model tests were applied to the soils improved by stone columns with cement additive, and the test results were compared to the values calculated by the analyses made by Finite Element Method [2].

In different types of soils improved by jet grout columns, the changes in uniaxial compression strengths were investigated by Baumann depending on the Water/Cement ratio (W/C) used for the formation of the columns. According

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to the results of the studies, the compression strength values obtained in sandy and gravelly soils were higher than the compression strength values in clayey, silty and organic soils; moreover it was observed that the compression strength increased in gravelly-sandy, sandy-silty and silty-clayey soils as a result of increasing the cement amount. [3]

Trevi studied the relationship between the uniaxial compression strength and the elasticity modulus of the jet grout columns. In the experimental studies, the samples taken from silty and silty-sandy soils were used, and it was concluded that the jet grout column strength is directly proportional to the modulus of elasticity. [4]

To evaluate the stress/deformation relationships of the mixtures produced with various elastic materials, the method called as two-phase mixture method was suggested by considering the importance of stress distribution [5]. This approach named as “homogenization method” in the numerical analyses of the composite materials was applied on the soil strengthened by pile-shaped columns to get the average modulus of elasticity and yield stress of the strengthened soil. Several model tests were applied on the soil strengthened by cement-added stone columns, and vertical settlement and horizontal deformation values were measured for inclined loading conditions. After comparing the results of the numerical analysis and the test results, it was determined that the suggested method presented good accuracy in predetermining the bearing capacity of the strengthened soil.

During an 18000 m^2 foundation excavation of an art gallery construction in Singapore, the strengthening process of lateral surfaces supported with sheet pile walls and diaphragm walls was explained, and it was shown that the deformations were reduced by using jet grout columns [6].

The use of jet grout columns was examined by Wong and Poh to prevent the movement in the diaphragm walls of lateral surfaces of the excavation during the basement floor excavation of attached buildings. As seen from the observational data, the jet grout columns formed behind the shoring wall caused the soil to move in the opposite direction and deformations on the diaphragm walls in the opposite direction of the excavation. Moreover, in this study, it was also shown that the bending moments of the diaphragm walls were reduced and the attached buildings had minor effects from the excavation as a result of using jet grout columns. [7]

Kirsch and Sondermann stated that the numerical simulation of deformation behavior played an important role in understanding the mechanical behavior of the soil. In this study, numerical analyses for different approaches were planned, and it was shown that the numerical modeling had great effect on obtaining a reliable and economic design of improvement. [8]

Gökalp and Düzceer investigated the jet grout application used for the foundation of the power transformation facility connecting the natural gas pipeline in Aliağa. In the study, some explanations were made about the details of the method such as the choice of jet grout technique, application system and grout injection pressure and about the design parameters such as the number and dimension of the nozzles, the bearing capacity of the formed columns and the rotation speed of the nozzles.

After applying many pre-parametric tests and pulling tests for the preplanned jet grout studies, the diameter of the required jet grout column and the required pressure to reach that diameter were determined. Moreover, some explanations were made related to the comprehensive quality control and guarantee research performed after the application by making coring, unity and loading tests. [9]

Bell et al. performed uniaxial compression tests in the laboratory on the core samples taken from the super jet columns. In the tests, 3, 7, 14 and 28-day compression strength values of 76 x 150 mm cylindrical samples were determined, and it was seen that the strength values of super jet columns increased as time passes and reached the real value at the 28^{th} day. [10]

Özsoy and Dursunoğlu suggested a new approximate calculation method for decreasing the liquefaction effects by using jet grouting and deep mixing techniques. The shear stress distribution obtained for identified unit areas as a result of an earthquake was modeled by calculating the shear modulus difference between soilcrete columns and the soil surrounding them. The efficiency of the suggested method was also determined by the aid of the JG applications performed in the site of Ford-Otosan Gölcük Facilities [11].

Bzowka carried out a numerical analysis of jet grouting application which had four stages of preliminary planning and mathematical formulation, defining the model parameters, confirmation and accuracy analysis. It was stated that the loads acting on the jet columns and the settlements can be calculated by the aid of the numerical analyses unlike the traditional analyses using empirical formulas. In this study, the problem was modeled with its real dimensions. In numerical analyses, the jet grout column, its effective zone and soil environment were modeled separately using Mohr–Coulomb model. As a result of this research, the results of the numerical analysis, experimental findings and the empirical solutions were all compared with each other. [12]

Racansky et al. studied the effects of the thickness of the retaining walls constructed by jet grouting using two and three dimensional analyses [13]. The deformations and the safety coefficients of the supported and unsupported walls were calculated, and additionally three dimensional analyses were performed for various supporting intervals.

The soil improvement using jet grout method was researched by Küsin in details, and the results were evaluated by the aid of the PLAXIS software program after performing analyses for different conditions of JG columns using Finite Element Method [14].

Nikbakthan and Osanloo studied the effects of grout pressure and grout flow on the physical and mechanical properties of jet grout columns by making in-situ production and measurements [15]. For this purpose, six JG column samples of different grout pressure and flow were placed at the Shahriar Dam site. There were taken cylindrical core samples from different sections of these columns. Then, these samples were tested in the laboratory with uniaxial compression, triaxial compression, direct shear, Brazilian indirect pulling and Schmidt hammer tests. According to the laboratory results and numerical studies, it was stated that as grout pressure and grout flow increased, the uniaxial compression strength increased logarithmically. Additionally, the jet grouting process considerably improves the cohesion and internal friction characteristics of the soil.

Nikbakthan et al. searched the results of the laboratory tests performed on six JG columns constructed at the Shahriar Dam site using various production parameters. The varying parameters can be listed as; rod pulling speed, rod rotation speed, water/cement ratio, grout pressure, grout flow, water pressure and flow, air pressure and flow. As a result of the experimental and in-situ tests, the relationships of these parameters with the diameters and the unconfined compressive strength values of the constructed JG columns were given. [16]

The effects of injection pressure, water/cement ratio, rod pulling speed and rod rotation speed on the performance of jet grout columns were investigated experimentally [1]. For this purpose, a system that can produce a jet grout column was designed and built in the laboratory, and then the behavior of the jet grout columns were researched parametrically in the laboratory for the first time in the literature. The test design and the evaluation of the test results were performed using an effective optimization technique named as Taguchi Method. The injection pressures of 20, 30 and 40 bars, the water/ cement ratios of 1.00, 1.25 and 1.50 percentages, the rotation speeds of 5, 10 and 15 rotation/min and the rod pulling speeds of 15, 30 and 45 cm/min were selected as the parameters of the tests. After the tests, the diameters and the heights of the jet grout columns produced in the laboratory were measured and their column structures were investigated by obtaining their unconfined compressive strengths using the cores of different dimensions which were taken from the columns and performing S/N and multi-variable variance analyses on them to determine the effects of the parameters on the diameter and unconfined compressive strength values of the columns. The section of this work related to the pulling and rotation speeds are explained in the following.

III. Experimental Study

A. Device and Materials Used in the Experimental Studies

JG Column Production System: A similar Jet-1 type JG column production system applied in site was designed for the laboratory and assembled inside the laboratory (Fig. 1). The main tools and devices of the test mechanism can be listed as:

- Injection pump
- Drilling rod of 4 cm thick and 90 cm length
- Conical end of 1.5 mm diameter with 2 nozzles
- Injection tank
- Rotating motor
- Up/down traction motor
- Mixer
- Test tank

The prepared test mechanism in the laboratory has the capacity of maximum 100 bars injection pressure, 2-30 rpm rotation speed, 5- 100 cm/min rod pulling. The 20 lt injection tank involves the grout mixture prepared by using the required water/cement ratio and jetted into the soil with constant pressure at once.

Fig. 1 Mapping nonlinear data to a higher dimensional feature space

Experiment Sand: In the experimental studies, the natural sandy soil provided from the surroundings of Konya was used. Grain size distribution curve was drawn after performing wet-sieve analysis using sieves in accordance with ASTM standards (Fig. 2). Some characteristics of the sand used for the tests are all given in Table I.

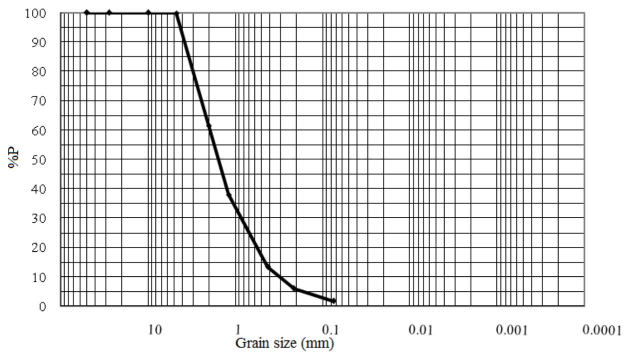

Fig. 2 Grain size distribution of the sand used in the tests

TABLE I
SOIL CHARACTERISTICS

Granulometry Parameters	Unit	Value
Sand Percentage	%	98
Silt+Clay Percentage	%	2
Fine Sand Percentage	%	53.60
Effective Diameter, D10	mm	0.30
Uniformity Coefficient, Cu	-	6.1
Gradation Coefficient, Cc	-	1.2
Soil Class (USCS)	-	SW
Specific Gravity, Gs	-	2.68
Maximum void ratio ,e_{max}	-	0.93
Minimum void ratio ,e_{min}	-	0.40
Relative Density, Dr	-	0.15

The sand used in the tests has a water content of 4% and was placed in a tank of 65 cm diameter, 110 cm height and

D_r=0.35 relative density (loose density) (Fig. 3). A sieving process from a specific height was carried out to reach this density. After the sand was placed, the rod was lowered to the tank bottom by rotating.

Fig. 3 Placing the sand into the experiment tank and the lowering process of the rod

TABLE II
EXPERIMENT PROGRAM

JG Production Parameters	1st Combination	2nd Combination	3rd Combination
Relative density (Dr)	0.35	0.35	0.35
Injection pressure (P) (bar)	20	20	20
Water/Cement rate (w/c)	1.0	1.25	1.5
Pulling speed (Vp) (cm/min)	10	30	45
rotating speed (Vr) (rpm)	5	10	15

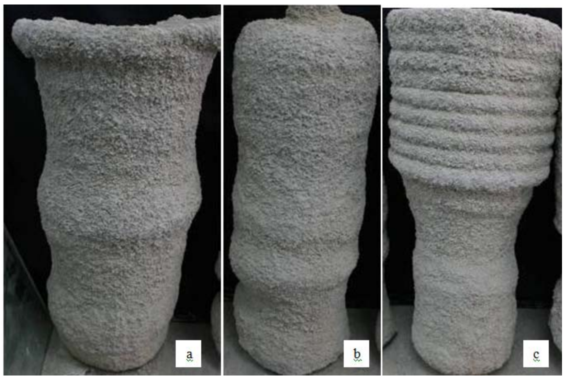

Fig. 4 JG columns produced in (a) 1st Combination (b) 2nd Combination (c) 3rd Combination

B. Experiment Program

In Jet Grout applications, there are many parameters affecting the performance of the columns. The main factors affecting the performance can be listed as; soil type, soil density/soil hardness, rod-pulling speed, rod rotating speed, injection pressure and Water/Cement ratio. JG columns were produced in 3 different combinations in the laboratory. The selected parameters and their values are given in Table II.

JG columns were produced in the experiment tank by laboratory type jet grout system in accordance with the program given in Table II (Fig. 4). After 28 days, the tanks were opened and the columns were taken out.

C. Experiment Results and the Evaluation

The JG columns produced with 3 different combinations of production parameters were taken out of the tank after 28 days, and the unity of the columns were observed after measuring the diameters and lengths of the columns. Cylindrical core samples of 5 cm diameter were taken using a core drilling machine to determine the compressive strength values of the columns (Fig. 5). The core samples were smoothened using a marble cutting machine to prepare the cylindrical test samples of specific diameters and lengths (Fig. 6).

Fig. 5 Taking cores from the columns

Fig. 6 The preparation process of the core samples

Unconfined compressive strength values were measured after performing unconfined compressive experiments on the prepared core samples. The average diameter, column length and unconfined compressive strengths of the JG columns produced in 3 different combinations are given in Table III.

The importance of choosing the parameters of Jet grout columns properly are clearly seen in Figs. 4, 5 and Table III. When the pulling and rotation speed increases; the unconfined compression strength of the columns decreases drastically.

According to the test results, increasing the pulling and rotation speeds causes to decrease the diameter of the columns slightly. However, too much pulling speed choice affects the integrity of the column (homogeneity) (Fig. 7) and it decreases the compressive strength to a large extent.

TABLE III
EXPERIMENT RESULTS

JG Production Parameters	Column Diameter (cm)	Column Length (cm)	Unconfined compressive strength MPa
1st Combination	30.0	72	12.0
2nd Combination	24.0	65	8.5
3rd Combination	22.0	69	2.5

Fig. 7 Effect of Pulling Speed on the Column Performance

IV. CONCLUSIONS

It is quite important that this study showed the practicability of the parametric studies on JG columns produced in the laboratory using a specially designed laboratory-type jet grout column system. In this study, the columns produced in 3 different combinations were compared with each other. The pulling speed and the grout pressure significantly affect the column performance. Therefore, the column production parameters should be controlled carefully during the in-situ applications. By the aid of the improved system, the studies for different soils and parameters continued within the context of the Ph.D. dissertation project. As a conclusion, it is expected to get quite important information related to the design stage and performance of the JG columns.

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