NEU PRESS

FEN ve MÜHENDİSLİK BİLİMLERİ DERGİSİ

Cilt/Vol: 7 Sayı/No: 3 Yıl/Year: 2025 Araştırma Makalesi/Research Article e-ISSN: 2667-7989

https://doi.org/10.47112/neufmbd.2026.106

Taguchi Yöntemi ile Optimize Edilen Jet Grout Kolonlarının Performansına İlişkin Laboratuvar Deneysel Çalışması

İbrahim Hakkı ERKAN[1*] Özcan TAN[1]**

[1] Konya Technical University, Faculty of Engineering and Natural Sciences, Department of Civil Engineering, Konya, Türkiye

Makale Bilgisi

Geliş Tarihi: 26.05.2025
Kabul Tarihi: 15.06.2025
Yayın Tarihi: 31.12.2025

Anahtar Kelimeler:
Jet grout kolon,
Taguchi yöntemi,
Zemin iyileştirme,
Jet grout enjeksiyon basıncı,
Jet grout çekme ve dönme hızı.

ÖZET

Bu çalışmanın temel amacı, jet grout (JG) yöntemiyle oluşturulan kolonların mekanik performansına etki eden üretim parametrelerinin belirlenmesi ve bu parametrelerin optimizasyonudur. Zayıf zeminlerde yapılaşmanın artmasıyla birlikte JG yöntemi, taşıma gücü artırımı ve zemin iyileştirmede sıklıkla tercih edilen bir teknik haline gelmiştir. Çalışmada, enjeksiyon basıncı, tij çekilme hızı, tij dönme hızı ve su/çimento (S/Ç) oranı olmak üzere dört üretim parametresi ele alınmıştır. Her parametre üç seviyede test edilmiş ve deneysel tasarım, Taguchi L9 ortogonal dizilimi ile gerçekleştirilmiştir. Özel olarak tasarlanmış laboratuvar tipi JG deney düzeneği kullanılarak toplam 18 kolon üretilmiştir. Kolonlardan alınan karot örnekleri ile serbest basınç dayanımı testleri yapılmış ve kolon çapı ölçümleri gerçekleştirilmiştir. Sonuçlar, kolon çapı üzerinde en etkili parametrenin %43 oranla enjeksiyon basıncı olduğunu; serbest basınç dayanımı üzerinde ise %36,5 oranla yine enjeksiyon basıncının en belirleyici değişken olduğunu göstermiştir. S/Ç oranı ve tij çekilme hızındaki artışlar dayanımı olumsuz etkilerken; düşük çekilme hızlarında ve yüksek dönme hızlarında daha homojen ve dayanıklı kolonlar elde edilmiştir. Kolon kesit analizleri, çekirdekten dışa doğru dayanımın azaldığını göstermiştir. Sonuç olarak, JG kolon performansının iyileştirilmesinde üretim parametrelerinin dikkatli seçimi kritik öneme sahiptir. Gelecek çalışmalarda farklı zemin türlerinde geniş ölçekli saha deneyleri önerilmekte; ayrıca çevresel etkileri azaltmak için alternatif bağlayıcı malzemelerin ve inovatif enjeksiyon uçlarının geliştirilmesi tavsiye edilmektedir.

A Laboratory Experimental Study on the Performance of Jet Grout Columns Optimized by Taguchi Method

Article Info

Received: 26.05.2025
Accepted:15.06.2025
Published: 31.12.2025

Keywords:
Jet grout columns,
Taguchi method,
Soil improvement,
JG injection pressure
JG pull out-rotataion speed.

ABSTRACT

The primary objective of this study is to investigate the influence of manufacturing parameters on the mechanical performance of jet grout (JG) columns and to optimize these parameters using statistical design. The increasing demand for infrastructure on weak soils has made JG a widely adopted ground improvement technique for enhancing bearing capacity and reducing settlement. Four major manufacturing parameters—grout pressure, rod pull-out speed, rod rotation speed, and water/cement (W/C) ratio—were examined at three levels using the Taguchi L9 orthogonal array design. A custom-designed laboratory-scale JG system was developed to replicate field conditions. A total of 18 JG columns were produced. Column diameter and unconfined compressive strength (qu) were measured on core samples extracted from each column. The results showed that grout pressure was the most influential factor on column diameter (43%) and also on unconfined compressive strength (36.5%). Higher W/C ratios and pull-out speeds led to decreased strength and column homogeneity, while increased rod rotation speed enhanced strength but slightly reduced diameter. Core sample analysis revealed a significant reduction in strength from the core center to the outer edges. Optimal performance was achieved with low pull-out speeds and moderate rotation rates. The study highlights the critical role of optimized parameter selection in improving JG column performance. Future research should explore larger-scale field experiments across varied soil types. Investigating eco-friendly binders and advanced nozzle designs is also recommended to enhance both environmental and mechanical performance.

To cite this article:
Erkan, İ.H. & Tan, Ö. (2025). A laboratory experimental study on the performance of jet grout columns optimized by Taguchi method. *Journal of Science and Engineering, 7*(3), 458-474. https://doi.org/10.47112/neufmbd.2026.106

***Sorumlu Yazar:** İbrahim Hakkı Erkan, *iherkan@ktun.edu.tr*
** Özcan TAN passed away on January 6, 2020. This study is dedicated to his cherished memory, *adres@bilgisi.yok*

INTRODUCTION

With the increase in population, expansion of industrial zones and acceleration of urbanization rate, it has become compulsory to construct both industrial and residential buildings on weak soils in terms of bearing capacity and settlement properties. Soft clay and silt, loose sand-gravel and peat soils create serious problems in construction projects with low bearing capacity and high settlement potential. In order to eliminate the bearing capacity and settlement problems and risks such as liquefaction due to the structures to be built on such soils, the application of ground improvement techniques is mandatory. Jet grouting (JG) method, which is a widely used ground improvement technique today, is an improvement method that stands out with its versatility and application flexibility in this field and has been successfully applied [1]. The JG method is a technique in which high modulus columns called 'soilcrete' are formed by injecting the water-cement mixture into the ground with high pressure and breaking the ground. With the application of this technique, the bearing capacity of the soils is increased, settlements and water permeability of the soil are reduced and the resistance of the soil against liquefaction is increased. This method has significant advantages such as being applicable in many different applications of geotechnical engineering, in a wide range of soil classes and under different conditions, being more economical than other alternative ground improvement methods and being able to be constructed in a shorter time.

The mechanical properties and performances of the columns formed by applying the JG method in the field under different soil classes and conditions vary considerably according to the application parameters of the method. Investigating the effects of manufacturing parameters on the performance of JG columns with field studies involves significant difficulties in terms of both cost and time [2] determined the performance of JG columns in soft clay soil in Al-Nasiriyah, Iraq, through a series of field and laboratory experiments. The researchers constructed JG columns in the field at different injection pressures and constant water/cement ratio (1.0) and took core samples from these columns. Unconfined compression and split tensile tests were performed on the samples to determine the cohesion and internal friction angles of the JG column specimens. The authors also determined the diameters of the columns formed at different injection pressures and the effects of curing time on the compressive strength (qu) of the columns. As a result of the study, it was determined that the JG method increases the bearing capacity of soft clay soils and the diameter of the column formed increases with increasing injection pressure. The authors also concluded that the field test results obtained by the authors are consistent with the theoretical values obtained [3-4].

In another parametric study, JG columns were constructed at different injection pressures, different water/cement ratios and different soil types [5]. The JG columns manufactured in the field were formed in clay soil, sand soil and alluvial soil. Injection pressures were selected as 400, 450 and 500 bar and water/cement ratios as 0.75, 1.00 and 1.25. During the injection process, the rotation speed of the rods was 15 rpm and the pull-out speed was 30 cm/min. Maximum column diameter was obtained in sandy soil and minimum column diameter was obtained in clay soil. The most homogenous columns were obtained in sandy soil. The unconfined compressive strength of the columns decreased with increasing water/cement ratio. Maximum qu value was obtained in sandy soil and minimum qu value was obtained in clay soil. Qu values up to 35 Mpa were obtained in sandy soil and 15 Mpa in clay soil. Columns with 37% and 26% larger diameters were obtained in sandy soils compared to clay and alluvial soils, respectively.

The effect of manufacturing parameters on the durability of JG columns against external influences is also important. As the injection pressure increases in the formation of the column, the homogeneity of the column may deteriorate while a larger diameter column is formed. Likewise, with a decrease in the water/cement ratio, columns with higher strength and more resistance to external influences can be obtained, while the diameter of the formed column may be small. JG columns produced at different pressures ranging from 300 to 400 bar and different rotational speeds in a low plasticity clay (CL) soil in the field [6]. They investigated the chemical stability of core samples taken from the produced columns in 1% sulphuric acid solution and the changes in unconfined compressive strength under wetting-drying cycles. As a result of the study, the resistance to chemical materials decreases significantly with the increase in injection pressure, while a mass loss of 20~25% occurs in the first cycles of soaking-drying cycles, while the rate of increase in mass loss decreases with the increase in the number of cycles. In addition, the homogeneity of the columns formed with the increase in the rotation speed of the rods was deteriorated.

JG columns are widely used in soil improvement applications in the world and in our country. However, when the studies in the literature are examined, it is seen that there are a limited number of laboratory scale studies on the effect of the change in the manufacturing parameters of JG columns on column properties [7-8]. The aim of this study is to investigate the effects of the manufacturing parameters of JG columns on the performance of the columns. The laboratory type JG machine used in the study was manufactured by the authors [9-10]. Within the scope of the study, the effect of the variation of the parameters such as injection pressure, rod pulling speed, rod rotation speed and water/cement ratio on the column diameter and unconfined compressive strength was investigated. Within the scope of the parametric study, Taguchi method, a powerful optimization technique, was used to design the experiment with a 3-level L9 orthogonal array with 4 different parameters [11,12].

MATERIALS AND METHODS

In the study, the soil medium in which the JG columns will be formed was selected as sand soil. The granulometry curve, index and physical properties of the sand used in the experimental study are given in Table 1 and Figure 1.

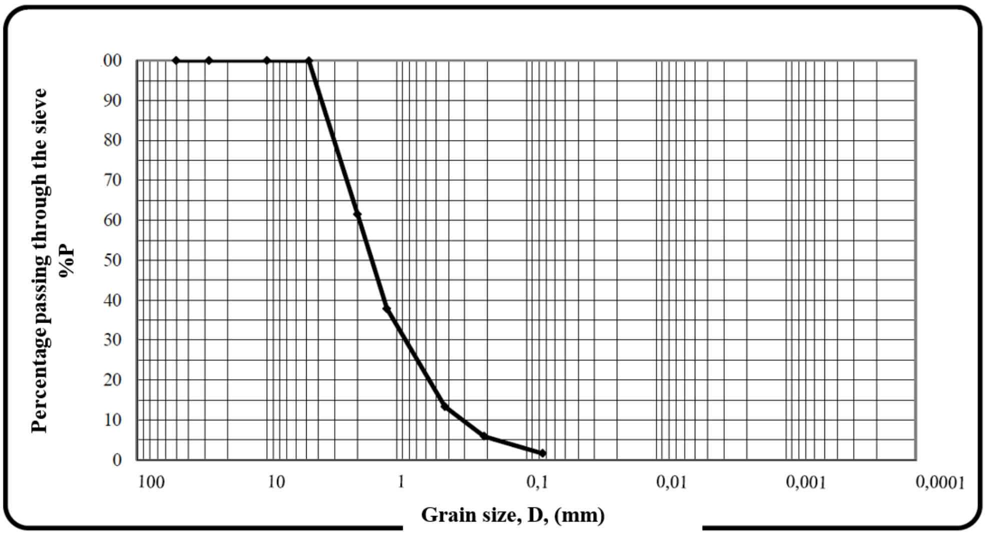

Figure 1
Granulometry curve of the sand used in the experimental study.

Table 1
Index and physical properties of the sand used in the experimental study.

Gravel (%)	0
Sand (%)	98
Clay+Silt (%)	2
Coefficient of uniform (C_u)	6.1
Coefficient of gradation (C_c)	1.16
Soil class (USCS)	SW
Specific gravity (γs, kN/m^3)	26.3
Maks. Void ratio (e_{max})	1.09
Min. Void ratio (e_{min})	0.38
Natural Void ratio (e)	0.88
Relative density (D_r)	0.35

Portland cement PKÇ32.5 was used to form the injection material. Injection material was prepared at different water/cement ratios and rheological properties of the prepared injections were determined. Within the scope of determination of rheological properties; setting start and end times, viscosity values and injection settling times were determined according to ASTM standards [13,14,15,16] (Table 2, Figure 2).

Table 2
Rheological properties of the injection material for different water/cement ratios .

W/C Ratio	Initial hydration setting *time (h)*	Final hydration setting *time (h)*	Flow time from Marsh funnel *(s)*	Sedimentation percentages *(%)*
1.00	10.50	20.45	30	20.2
1.25	30.25	38.75	27	30.1
1.50	35.50	44.50	25	37.1

a) b) c)

Figure 2
Determination of rheological properties of the injections a) Vicat test b) Marsh funnel test c) Sedimentation test .

The sand to be used in the formation of JG columns was prepared with a natural water content of 4.5% and then sieved from a fixed height in cylindrical tanks with a relative density of Dr=0.35 (Figure 3a). The grout used in the parametric study was prepared with the help of a mixer according to the determined water/cement percentages (Figure 3b).

a) b)

Figure 3
a) Placing the sand soil to be used in the experiments in the tank b) Preparation of the injections.

Manufacturing of JG Column Machine in Laboratory Scale

The similar JG machine used in real scale in the field was manufactured in the laboratory environment by the authors. The JG column machine designed in the laboratory scale was designed to fulfil all the features of the field type jet grouting machine in the laboratory environment and in the laboratory scale. The main components of the system that performs JG application in the field are drilling machine, pump, mixer and cement silo (Figure 4).

Figure 4
Jet grouting field application machine components [17].

The equipment designed in the laboratory includes the components listed below.

- Injection pump

- 90 cm long drill rod

- 1.5 mm thick double nozzle injection tip

- Injection chamber

- Motor rotating the drill rod
- Pulling motor pushing the drill rod up and down
- Injection mixer
- Control unit
- Test tank

The JG machine designed in the laboratory environment has a capacity of 100 bar. The rotation capacity of the rod is between 2~30 rpm, the pulling speed capacity is between 5~100 cm/min and the injection storage capacity of the machine is designed as 20 liters. After the injection to be used in the experimental study is prepared, it is transferred to the injection hopper without waiting and injected into the ground with pressure. During the experiment, injection pressure is an important parameter for the formation of columns, and separate manometers were placed on the pressure-controlled pump and injection transmission line to ensure that the injection is transmitted under constant pressure. The experimental set, pump and rod rotation-pull motors are shown in Figure 5. The diameters of the nozzles that allow the injection to exit from the rod end and the fluid flow outlet velocities were controlled with the help of water (water jet) before the experiment. Images of the nozzles at different injection pressures selected in the parametric study are given in Figure 6.

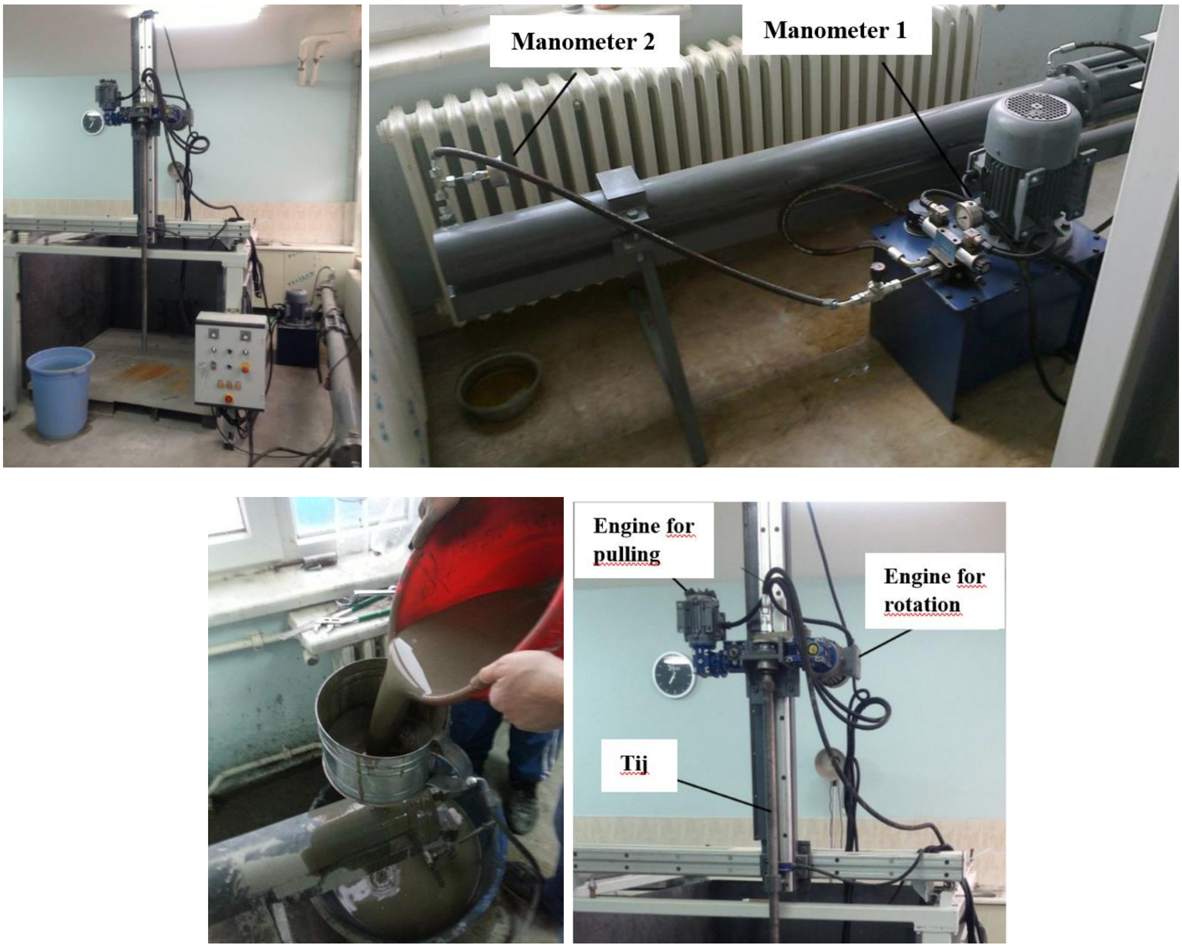

Figure 5
Laboratory scale JG column machine experimental set.

Figure 6
Exit conditions of the cross-section from the nozzles (20 bar, 30 bar, 40 bar).

Taguchi Method and Experimental Design

The Taguchi method, developed by the Japanese statistician Genichi Taguchi (Source), is a powerful optimization method used especially for quality control in experimental studies and manufacturing and to improve manufacturing processes. The most important advantages of this method are reducing the number of experiments, increasing quality in product development and improving performance outputs. In experimental studies and quality control processes related to product manufacturing, the most important goal is to make evaluations about the target result with the minimum number of experiments or production.

In the study where the factors affecting the performance of JG columns were investigated by Taguchi method; firstly, the purpose of the study and the performance criteria of JG columns were determined by defining the problem. In the second stage, the parameters affecting the performance of JG columns and the levels of these parameters were selected. In the study, 4 parameters and 3 levels for each parameter were selected. For these selected parameters and levels, L9 Taguchi orthogonal array experimental design table was used. Experimental studies were carried out in accordance with the determined orthogonal index. As a result of the statistical evaluations of the experimental results, Signal/Noise (S/N) ratios were calculated, the degree of influence of the parameters on the experimental results was determined and the optimum levels of the parameters were obtained. Finally, the results were checked by performing verification experiments for the determined optimum levels.

In the experimental study, a special laboratory-type JG test system was designed that allows the production of JG columns in a laboratory environment. This system has been developed in such a way that it can perform all the functions of a real jet grouting system in the field. In this way, the production of JG columns in the laboratory has been made possible and an experimental programme containing the manufacturing parameters used in practice has been prepared. The most important parameters affecting JG column manufacturing;

- Grout Pressure (P)

- Pulling speed of the JG column system drill rod (V)

- Rotational speed of the JG column system rod (D)

- Water/cement ratio for injection (W/C)

is as follows.

The levels of the determined parameters were determined by considering the condition of the test columns made in the laboratory at the first stage, the evaluation of the parameters applied in the field and the laboratory conditions and are given in the table below (Table 3).

Table 3
Parameters and their levels used in the experimental study.

	P1	P2	P3	P4
	Pressure *(bar)*	**W/C Ratio**	**Pulling Speed *(cm/min.)***	**Rotation Speed *(rpm)***
Level 1	20	1.0	15	5
Level 2	30	1.25	30	10
Level 3	40	1.5	45	15

After the parameters to be used in the experiments and the levels of these parameters were determined, the L9 experimental design table was created and the experimental program was finalized (Table 4). For the study, each experiment was planned to be carried out with 2 repetitions and 18 JG columns were produced in total.

Table 4
L9 Experimental Design Table in the experimental study.

JG Test No	Pressure, P, *(bar)*	W/C Ratio	Pulling Speed *(cm/min.)*, V	Rotation Speed *(rpm)*, D
1	20	1.00	15	5
2	20	1.25	30	10
3	20	1.50	45	15
4	30	1.00	30	15
5	30	1.25	45	5
6	30	1.50	15	10
7	40	1.00	45	10
8	40	1.25	15	15
9	40	1.50	30	5

Before starting the experiments specified in the L9 design table, a series of calibration experiments were carried out on the JG system to check the proper operation of the system. Before proceeding to the creation of JG columns in the laboratory environment in accordance with the parameters specified in the experimental program, test columns were produced to simulate the application in the field. This process is a critical stage in terms of testing the reliability and accuracy of the system. The visuals of the first test columns are given in Figure 7. As a result of the evaluations and improvements, the system was modified and the columns in the L9 experimental design table were created (Figure 8).

Figure 7
Initially produced test columns under laboratory conditions.

Figure 8
Stages of producing JG columns in laboratory environment.

RESULTS AND DISCUSSION

Firstly, the diameter and height of the JG columns produced according to the Taguchi experimental design table were measured. Then, unconfined compressive strength tests were performed on the core samples taken from the columns and the mechanical strengths of the columns were analyzed. In the analysis of mechanical strengths, S/N ratios were determined using Taguchi Method and variance analyses were performed. As a result of these analyses, the effects of the test parameters on the unconfined compressive strength and column diameter variation were determined and the optimum parameter levels at which the diameter and strength are maximum were determined. The results obtained were analyzed comprehensively to evaluate the performance and efficiency of the system.

In the first stage of the experimental study, at the end of the 28-day waiting period following the production of JG column samples, the diameter and height measurements of the columns removed from the moulds were made. The visuals of the columns produced in the first group are presented in Figure 9 and Figure 10. The average diameter and height values of the columns produced in two repetitions are given in Table 5. As can be seen from the diameter and height values obtained, the diameter and height values of the columns produced in two repetitions were found to be very close to each other. This situation is important in terms of placing the soil at the desired tightness and showing that no systematic error was made during the formation of the columns.

Table 5
Average diameter and height of JG columns constructed according to the experimental design.

JG Column No	Average JG Column Diameter *(cm)*		Average JG Column Height *(cm)*	
	Test 1	Test 2	Test 1	Test 2
1	30.1	34.4	72	71
2	23.8	26.1	65	66
3	23.9	25.5	69	70
4	30.0	25.9	65	68
5	39.5	43.3	58	65
6	37.5	38.4	56	59
7	29.7	29.8	65	60
8	35.1	45.1	51	53
9	47.1	48.2	52	60

Figure 9
First group of JG columns produced according to L9 design.

Figure 10
Second group of JG columns produced according to L9 design.

When the 1st group columns are analyzed (Figure 9), it is seen that columns 1, 6 and 8, where the pulling speed is low (15 cm/min), have a more homogeneous diameter and a more compact structure compared to the other columns. On the other hand, in columns 3, 5 and 7, where the shrinkage rate was high (45 cm/min), it was observed that homogeneity in the column structure and diameter could not be achieved, resulting in the formation of spiral (leaf) structures. This situation indicates that the injection material is not homogeneously distributed in the soil and that the mixing and tearing in the soil is not sufficient. Therefore, it is clearly demonstrated that the shrinkage rate is a critical parameter in the performance of JG columns. Partial spiraling was observed in columns 2, 4 and 9 where the shrinkage velocity was moderate (30 cm/min) (Figure 9). Keeping the shrinkage rate at low levels prevented the formation of spiral structures and created more compact and homogeneous columns. Spiraling was also observed in column 9 and this is attributed to the extremely low rotational speed of the rod in design 9 and the grout pressure of 40 bar. The high grouting pressure adversely affects the column homogeneity and leads to the formation of spiral structures. This can be explained by the inability of the grouting pressure to distribute the material homogeneously in the soil and cause irregularities around the column.

At least three cylindrical core samples were taken from each column after measurements such as diameter and height of the columns produced in accordance with the test program (Figure 11). In the production of JG columns, very successful cylindrical samples were obtained from the columns obtained for the designs with a rod pulling speed of 15 cm/min and 30 cm/min; disintegration and fragmentation were minimal in these columns. However, it was very difficult to obtain cylindrical core samples from the columns obtained for the designs with a rod pulling speed of 45 cm/min due to the spiral structure and lack of homogeneity, and samples of the desired diameter and length could not be obtained from some columns. In these columns, serious disintegration and fragmentation were observed during the coring process. This situation is discussed in more detail in the following sections. The core samples were carefully cut to a height/diameter ratio of 2 or close to 2 (Figure 12) and subjected to unconfined compression strength tests (Table 6).

Figure 11
Taking core samples from JG columns produced according to L9 design.

Figure 12
Core samples taken from JG columns produced according to L9 design.

Table 6
Unconfined compressive strength values of core samples taken from JG columns and S/N ratios obtained.

Column No	Avg. Unconfined Compressive Strength *(MPa)*	S/N Ratio
1	13.7	22.6
2	8.6	18.6
3	3.0	9.4
4	10.7	20.5
5	1.2	0.9
6	5.1	13.8
7	2.4	7.5
8	3.1	9.8
9	0.71	-3.0

In order to observe the change in the structure of the JG columns formed in the laboratory, cross sections were taken from the center of the columns along the radius and cross-sectional examinations were carried out (Figure 13). In these examinations, it was found that the columns formed in the laboratory environment had similar characteristics with the situations encountered in applications. It was observed that three different zones were formed in the soil environment after JG application [18]. The first zone is the 'well cemented zone' starting from the center of the column, where the cement ratio is the highest and the compressive strength reaches the maximum level. This zone is also defined as the jet grout body. The second zone is the 'poorly cemented zone' where the cement ratio and soil-cement mixture decrease as it moves away from the center. The outermost part of this zone is called the transition zone. The third zone is the 'natural soil zone' which is located beyond the transition zone and is not affected by JG application.

By matching the results of the unconfined compressive strength tests performed on core samples taken from JG columns with the cross-sectional examinations performed in the laboratory, it was determined that the strength decreases with distance from the center of the column. However, due to the small diameter of the columns produced in the laboratory, core samples could only be taken from the well cemented area. If larger diameter columns are produced, it is predicted that the unconfined compressive strength of laboratory-scale columns will decrease more significantly with distance from the center of the column [18].

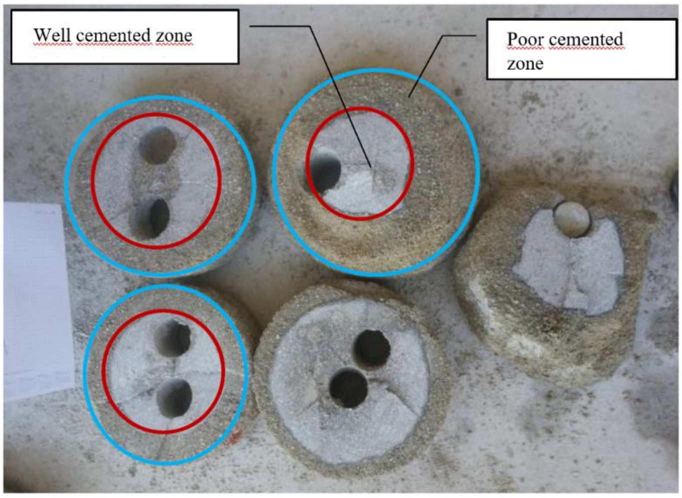

Figure 13
Cross-section samples taken on JG columns and cross-section analyses.

Evaluations with Taguchi Method

S/N analyses and multivariate analyses of variance (ANOVA) were performed using Taguchi Optimization technique in order to determine the effects of injection pressure, water/cement ratio, drawing speed and rotational speed on column diameter and unconfined compressive strength change in JG columns. In this context, the studies and statistical evaluations carried out to determine the optimum parameter ratios are presented in detail in Table 7.

Table 7
S/N values calculated for JG Column diameter variations

	Average Column Diameter *(cm)*		
Column No	**Experimental Set 1**	**Experimental Set 2**	**S/N Ratio**
1	30.1	34.4	30.1
2	23.8	26.1	27.8
3	23.9	25.5	27.7
4	30.0	25.9	28.7
5	39.5	43.3	32.3
6	37.5	38.4	31.5
7	29.7	30.0	29.3
8	35.1	45.1	31.9
9	47.1	48.22	33.6
Average S/N Ratio			30.3

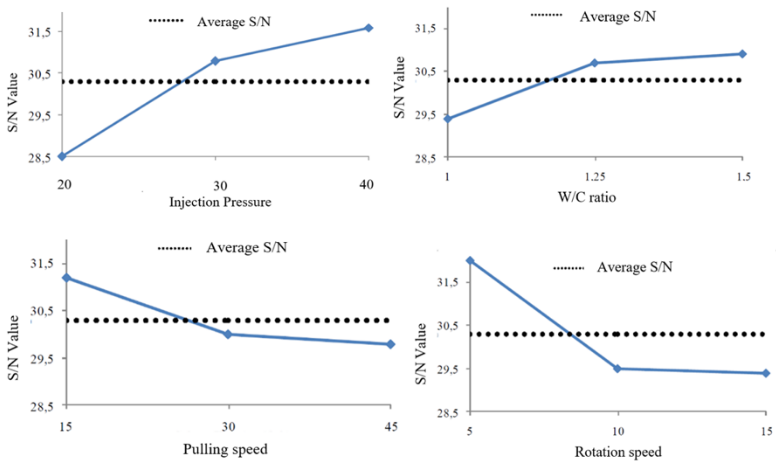

Figure 14
Effect plots of parameters for diameter changes of JG columns.

From the effect graphs of the parameters effective on the JG column diameter changes (Figure 14), it was determined that the column diameter increased significantly as the injection pressure and water/cement ratio increased, whereas the increase in shrinkage rate and rotational speed caused a slight decrease in the column diameter.

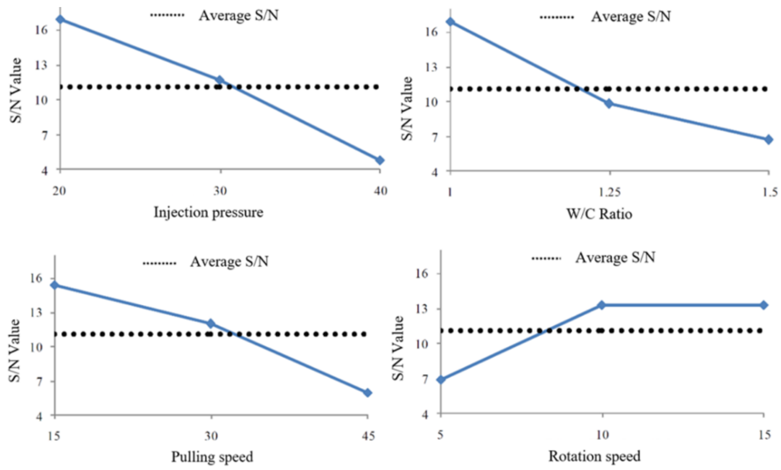

Figure 15
Effect plots of parameters on the unconfined compressive strength variations of JG columns.

JG columns from the effect graphs of the parameters that are effective on the changes in unconfined compressive strength (Figure 15), a decrease in unconfined compressive strength is observed as the injection pressure, water/cement ratio and shrinkage rate increase, whereas an increase in rotational speed leads to an increase in unconfined compressive strength.

The effect of the parameters as a result of ANOVA analyses are given in Figure 16 and Figure 17. As can be seen from Figure 16 and Figure 17, the most effective parameter on the column diameter is the injection pressure with 43%. The second most effective parameter is the rotational speed of the rod with 36%. It was also found that the column diameter increased significantly and with a slope close to linear with the increase in injection pressure. As the rotational speed of the rod increased, a significant decrease in the column diameter was observed, especially up to level 2 (10 rpm).

Increasing the rotational speed of the JG column system has a positive effect on the strength, but higher speeds lead to a reduction in the column diameter and loss of homogeneity. This indicates that the rotational speed should be kept at an optimum level. The effect of W/C ratio on the column diameter was determined as 12% and the effect of tensile speed was determined as 9.5%. According to the results of the analysis of variance for the unconfined compressive strength, the most effective parameter on the strength is the injection pressure with 36.5% (Figure 17). The second most effective parameter is the W/C ratio with 27%. The increase in water/cement ratio positively affected the increase in column diameter, but decreased the unconfined compressive strength. This decrease can be explained by the fact that high water content weakens the binder material and adversely affects the cementation process. The increase in the injection pressure and W/C ratio causes a significant decrease in the unconfined compressive strength with a slope close to linear. The effect ratio of the JG system rod pulling speed on the unconfined compressive strength was found to be 23% and the effect ratio of the rotational speed was found to be 14%.

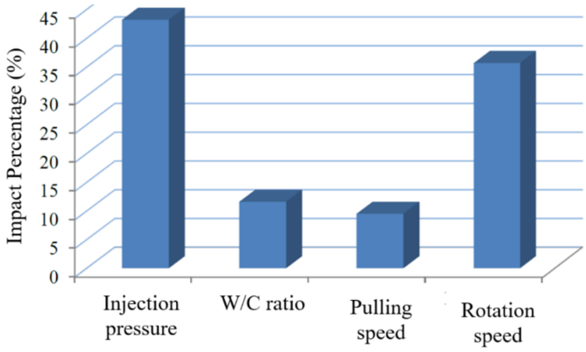

Figure 16
Effect ratios of parameters on JG column diameter variation

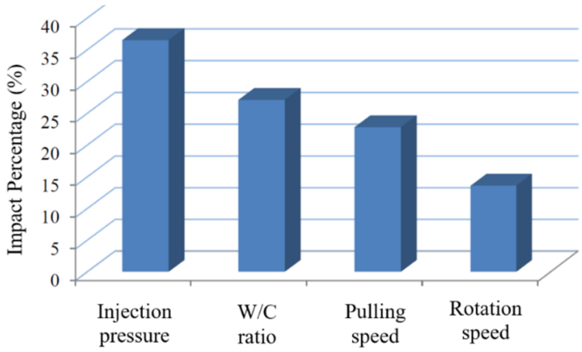

Figure 17
Effect ratios of parameters on unconfined pressure changes in JG columns

CONCLUSIONS

In this study, the column diameter formation and unconfined compressive strength performances of JG columns fabricated in the laboratory were investigated. The geometrical and mechanical properties of JG columns depend significantly on the careful selection of the parameters used during fabrication. In this study, the effects of grouting pressure, water/cement ratio (W/C), rod pull-out speed and rotational speed parameters on the formation of JG columns were analyzed. The results obtained showed that the most effective parameter on the column diameter was the injection pressure with 43%, followed by the rod rotation speed with 36%. It was concluded that as the injection pressure increases, the column diameter increases significantly and with a slope close to linear, but high rod rotation speeds lead to a decrease in diameter. The water/cement ratio parameter had a 12% effect on the column diameter change and the rod rotation speed parameter had a 9.5% effect on the result, and the effects of these two parameters on the column diameter change were found to be relatively lower. In terms of the change in unconfined compressive strength, the injection pressure was again the most effective parameter with 36.5%, followed by the water/cement ratio with 27%, the rod pull-out speed with 23% and the rod rotation speed with 14%.

While the increase in injection pressure and water/cement ratio caused a decrease in the unconfined compressive strength of the JG column core samples, the increase in the rotational speed of the rod increased the strength value. In the JG column system, keeping the rod pulling speed low during fabrication increased the column homogeneity and enabled high quality core samples to be obtained. These findings clearly demonstrate the importance of optimizing the manufacturing parameters and their interactions in the performance of JG columns.

For future research, it is recommended to investigate the parameters affecting the performance of jet grout columns over a wider range. In particular, studies on different soil types (sand, clay, alluvium, peat, etc.) and different field conditions will increase the generalizability of the method. Furthermore, innovative injection nozzles and alternative injection techniques should be developed to minimize the negative effects of high injection pressure on column homogeneity. Considering that the strength can be increased by reducing the water/cement ratio, studies on low environmental impact cement types or alternative binder materials are important for environmental and economic sustainability. In addition, three-dimensional simulations and visualization techniques can be used to better understand the effects of shrinkage rate and rotational speed on column diameter and homogeneity. Large-scale field experiments should be carried out to determine the optimum levels of shrinkage and rotational speeds. Furthermore, research examining the effects of additives to improve the chemical resistance of jet grout columns can make significant contributions to the long-term performance of the columns. Finally, the application of the Taguchi optimization method for different experimental designs will allow for a more in-depth analysis of the interactions of parameters. Such studies will be an important source of information for both academic and industrial applications.

Ethical Statement

This study is derived from the Ph.D. dissertation of Dr. İbrahim Hakkı ERKAN. His esteemed doctoral advisor, Prof. Dr. Özcan TAN, passed away on January 6, 2020. This work is dedicated to the cherished memory of Prof. Dr. Özcan TAN, who will always be remembered with deep respect and gratitude for his academic legacy, guidance, and profound humanity. This study was supported as part of the Ph.D. dissertation project of İbrahim Hakkı Erkan by the Scientific Research Projects (BAP) Coordinatorship of Selçuk University. The authors would also like to express their gratitude to TÜBİTAK for their valuable support.

Author Contributions

Research Design (CRediT 1) İ.H.E. (%70) – Ö.T. (%30)
Data Collection (CRediT 2) İ.H.E. (%80) – Ö.T. (%20)
Research - Data Analysis - Validation (CRediT 3-4-6-11) İ.H.E. (%60) – Ö.T. (%40)
Writing the Article (CRediT 12-13) İ.H.E. (%90) – Ö.T. (%10)
Revision and Improvement of the Text (CRediT 14) İ.H.E. (%100) – Ö.T. (%00)

Financing

This study was supported by the Selçuk University Scientific Researcher Project Coordinatorship project coded 11101027.

Sustainable Development Goals

Sustainable Development Goals: Not supported.

REFERENCES

[1] E. Güler, G.G. Seçilen, Jet grouting technique and strength properties of jet grout columns, *Journal of Physics: Conference Series*. 1928 (2021), doi:10.1088/1742-6596/1928/1/012006

[2] A. M. Al-Kinani, M.D. Ahmed, Field study of the effect of jet grouting parameters on strength based on tensile and unconfined compressive strength, *IOP Conference Series Materials Science and Engineering*. 737 (2020), 012083. doi:10.1088/1757-899x/737/1/012083

[3] J. K, Mitchell, The properties of Cement-Stabilised Soils, in: *Proceeding of Residential Workshop on Materials and Methods For Low Cost Road, Rail, and Reclamation Works*, Leura, Australia, Unisearch Ltd. 1976: pp:365-404

[4] G. G. Balmer, Shear Strength and Elastic Properties of Soil-Cement Mixtures Under Triaxial Loading, in: *Proceedings of American Society for Testing Materials by Portland Cement Association*, Research and Development Laboratories,USA, 1958: pp.1187-1204.

[5] M. Cinar, Investigation of mechanical and physical features of cementitious jet grout applications for various soil types, *Buildings*. 13 (2023), 2833. doi:10.3390/buildings13112833

[6] M.F. Hasan, H.F. Hasan, A.A. Mahdi, H. Canakci, Effect of jet grouting construction parameters on durability and strength properties of Full-Scale Clayey Soil-Cement Pile, *Soil Mechanics and Foundation Engineering*. 61 (2024), 483–490. doi:10.1007/s11204-024-10001-z

[7] A. Senkaya, E.B. Toka, M. Olgun, Effects of cement grout characteristics on formation and strength of jet grouting columns, *Arabian Journal for Science and Engineering*. 47 (2022), 13035–13047. doi:10.1007/s13369-022-06678-9

[8] M. Olgun, A. Kanat, A. Senkaya, I.H. Erkan, Investigating the properties of jet grouting columns with fine-grained cement and silica fume, *Construction and Building Materials*. 267 (2020), 120637. doi:10.1016/j.conbuildmat.2020.120637

[9] İ.H. Erkan, Experimental investigation of affecting factors on performance for jet grout columns, PhD Dissertation, Selcuk University, Graduate School of Natural Sciences, Konya, 2014.

[10] İ.H. Erkan, Ö. Tan, The effect of pulling and rotation speed on the jet grout columns, *International Journal of Civil Environmental Engineering*. 10 (2017), 1690–1694.

[11] G. Taguchi, Introduction to quality engineering: designing quality into products and processes, 4th edn. *Asian Productivity Organization*, Tokyo, 1988.

[12] G Taguchi, S.Chowdhury, Y Wu, Taguchi's quality engineering handbook. *John Wiley & Sons Inc*, Hoboken, NJ, USA, 2004.

[13] ASTM C136/C136M, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, *ASTM International*, West Conshohocken, PA, USA, 2019.

[14] ASTM D7928, Standard Test Method for Particle Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis, *ASTM International*, West Conshohocken, PA, USA, 2017.

[15] ASTM C 150/C 150M, Standard Specification for Portland Cement—Type I., *ASTM International*, West Conshohocken, PA, USA, 2021.

[16] ASTM D2166, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, *ASTM International*, West Conshohocken, PA, USA, 2016.

[17] Erktaş Zemin İnşaat Ltd.Şti., Jet Grout,(2017), https://www.erktas.com/faaliyet-alanlari/jet-grout/

[18] A. L. Garassino, Design Procedures for Jet Grouting, *Seminar organised by THL Foundation Equipment Pte., Ltd., and Gaggiotti,* Far East Singapore, 15–48, 1997.