Development of the Jet Grouting Method: Evolutionary History, Mechanism Insights, Innovative Approaches, and Future Prospects

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ABSTRACT: The development of the jet grouting method has been a significant breakthrough in the field of geotechnical engineering. This construction method was initially developed in Japan in the 1960s and has undergone various improvements to enhance its effectiveness and efficiency. The jet grouting method involves the injection of a cement-based grout material into the ground through a high-pressure jet. It has many excellent features, such as a wide range of applicable soils, high improvement strength, and the ability to construct using small-diameter boreholes. This technique enables the creation of a solid column of grout material that can provide support to unstable soil or rock formations. However, the quality of the improved ground is influenced by various factors, including the quality of the injection flow, the lifting speed, the rotation frequency, and the soil conditions. Over the years, there have been efforts to develop new construction methods that can improve the performance of the jet grouting method. These efforts have led to the development of advanced equipment and techniques that can achieve higher grouting pressures and faster injection rates, resulting in a more efficient and cost-effective construction process. In this paper, the history of the development of the jet grouting method will be reviewed, and the basic improvement mechanism of the method and case studies that the authors have worked on will be discussed. Furthermore, the development of new methods and future challenges and prospects for the jet grouting method will be discussed.

KEYWORDS: Jet Grouting, V-Jet Method, Rapidjet Method, and Jet Wave Monitoring System.

1. INTRODUCTION

The jet grouting method is a ground improvement method that creates improved ground by eroding and mixing the soil using a high-pressure injection of cement-based hardening materials. It has many excellent features, such as a wide range of applicable soils, high improvement strength, and the ability to construct using small-diameter boreholes. However, the quality of the improved ground is susceptible due to the quality of the injection flow, the lifting speed and rotation frequency, and the influence of the soil conditions (Wang et al., 2013; Hai et al., 2019; Chao et al., 2019; Cheng et al., 2023; Saelao et al., 2023; and Neaupane et al., 2023). It is always difficult to ensure that the improved ground with a uniform diameter is created. Furthermore, a trial test is often carried out to confirm the quality of the improved ground. Therefore, the jet grouting method requires not only efficient eroding and mixing of the soil but also an accurate assessment of the quality of the improved ground for design and construction (Sarkar et al., 2022; Yamazaki et al., 2023). In this paper, the history of the development of the jet grouting method will be reviewed. The basic improvement mechanism of the method we have worked on will be discussed, and the development and deployment of new methods will be reported. Furthermore, future prospects for the jet grouting method will be provided in the paper.

2. HISTORY OF JET GROUTING METHOD

The jet grouting method originated in Japan in the 1960s and has undergone continuous development and evolution. Currently, many methods have been implemented into practice and are extensively used in various construction sites.

The history of the development of the jet grouting method has been summarized by Japanese developers in technical journals and other publications. However, for a more objective perspective, the following summary of the jet grouting history is cited from the overseas technical book titled "Jet Grouting - Technology, Design and Control" (Croce et al., 2014).

The history of jet grouting in Japan is said to have begun in the late 1960s when researchers started studying the use of high-pressure jets as a tool for ground improvement. They developed the high-pressure jet grouting technology based on their experience with rock-cutting technology. They aimed to create cement solidification bodies within the ground by injecting hardening materials at high pressure through pre-drilled boreholes, cutting the ground with fluid, and mixing the materials at a designated location. With the confidence in the potential of jet grouting for ground improvement, the researchers subsequently developed various jet grouting methods. The technology known as the Japanese Chemical Churning Pile (CCP) method initially used chemical stabilizers as hardening materials, but it was later replaced with cement slurry. The advanced version of the Jumbo Special Pile (JSP) method, which became the prototype for the current Jumbo Special Grout (JSG) method, was developed with the aim of expanding the effective diameter of cylindrical improvement bodies, and it covered the injection of cement slurry with compressed air. Around the same time, a different system, which later became known as the Column Jet Grouting (CJG) method, was developed. This system involved eroding the ground with high-speed water jets and compressed air, followed immediately by filling the space with cement slurry from a lower nozzle. Over the next few decades, construction techniques were greatly improved, and private companies, such as specialized construction firms, took the lead in developing and implementing many jet grouting methods. This progression has persisted, leading us to the present day.

The jet grouting technique began in Japan and is widely recognized around the world. During the early 1970s, a notable event known as the "International Competition for the Stabilization of the Leaning Tower of Pisa" brought Japan's jet grouting technology to the attention of European companies, particularly those from Italy. An agreement was reached between the Italian companies and the CCP technology development company, and the technology began to spread throughout Europe. Later, the column jet grouting technique was introduced from Japan to Europe. Initially, jet grouting was generally applied as a means of improving the ground characteristics of large structural foundations, and it became popular in Italy, Germany, and the United Kingdom (UK) in the 1980s. It was subsequently widely accepted in Europe as a reliable soil improvement technique. Its applications expanded significantly to include foundations, excavations, tunnels, water barriers, underpinning, among others. In the United States, it was introduced in the early 1980s but had a "sluggish start", mainly because of perceived legal risks connected to the unknown technology.

However, it has since been recognized as a practical and cost-effective solution for many challenging situations, such as excavation support, groundwater barriers, foundation improvement for preventing the inflow of contaminants, bridge protection against scour, slope stability, and underpinning of existing structural foundations. It has gained popularity in the United States and Canada. During the same period, it became popular in most South American countries, particularly in Brazil, and now the jet grouting technique is used worldwide. Figure 1 shows the schematic diagram of the general jet grouting method used today, and Figure 2 illustrates the typical construction procedure of the jet grouting.

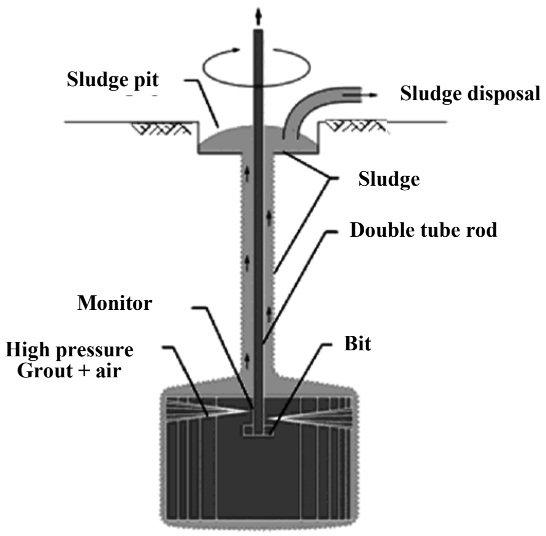

Figure 1 Conceptual diagram of the jet grouting method (Shinsaka et al., 2013)

3. BASIC IMPROVEMENT MECHANISM OF JET GROUTING METHOD

3.1 Injection Method

In the historical evolution of the jet grouting technology, the most important elements of each jet grouting technique are the type and number of fluids injected into the ground. Today, the available technologies are divided into three main injection styles based on the number of fluids injected into the ground, named single, double, and triple fluid systems, as shown in Figure 3.

Single fluid system: The water-cement (W-C) grout is injected into the ground through one or more nozzles. In this case, soil remoulding and subsequent cementation are both caused by the same fluid.

Double fluid system: Typically, the injected fluid is a cementitious material, and its injection is enhanced by minimizing energy loss through the use of a coaxial air jet that surrounds the injection. The air jet is injected from a coaxial annular nozzle positioned around the injection nozzle. Both the mixing with the soil and the subsequent hardening are achieved using the same fluid.

Triple fluid system: Typically, the fluid that is injected is a mixture of water and cementitious hardening material. High-speed jet water is supplied from a nozzle located at the top of the monitor, and soil eroding and mixing are carried out by the coaxial air jet flow. The cementitious hardening material is supplied from another nozzle located at the bottom of the monitor. It blends with the eroded and mixed soil, leading to the process of hardening.

The jetting method has evolved during the development of the technology and is closely related to the performance of high-pressure pumps, contributing to the expansion of improvement diameter along with the development of the method. For example, the development of high-performance high-pressure pumps has made it possible to jet hardening material at high pressure and large discharge. Consequently, this has led to the enlargement of the improvement diameter and the acceleration of construction.

3.2 Basic Improvement Mechanism

In the process of the jet grouting improvement, the fluid (hardening material or water) is discharged from the nozzle placed on the monitor. This fluid crosses the space formed between the rod (monitor) and the original ground, causing erosion of the ground. The ground can only be eroded if the fluid velocity is high enough to collide with the original ground. The improved bodies are formed by the mixing of a composite fluid composed of groundwater, cut soil particles, and jet fluid in a space filled with the composite fluid.

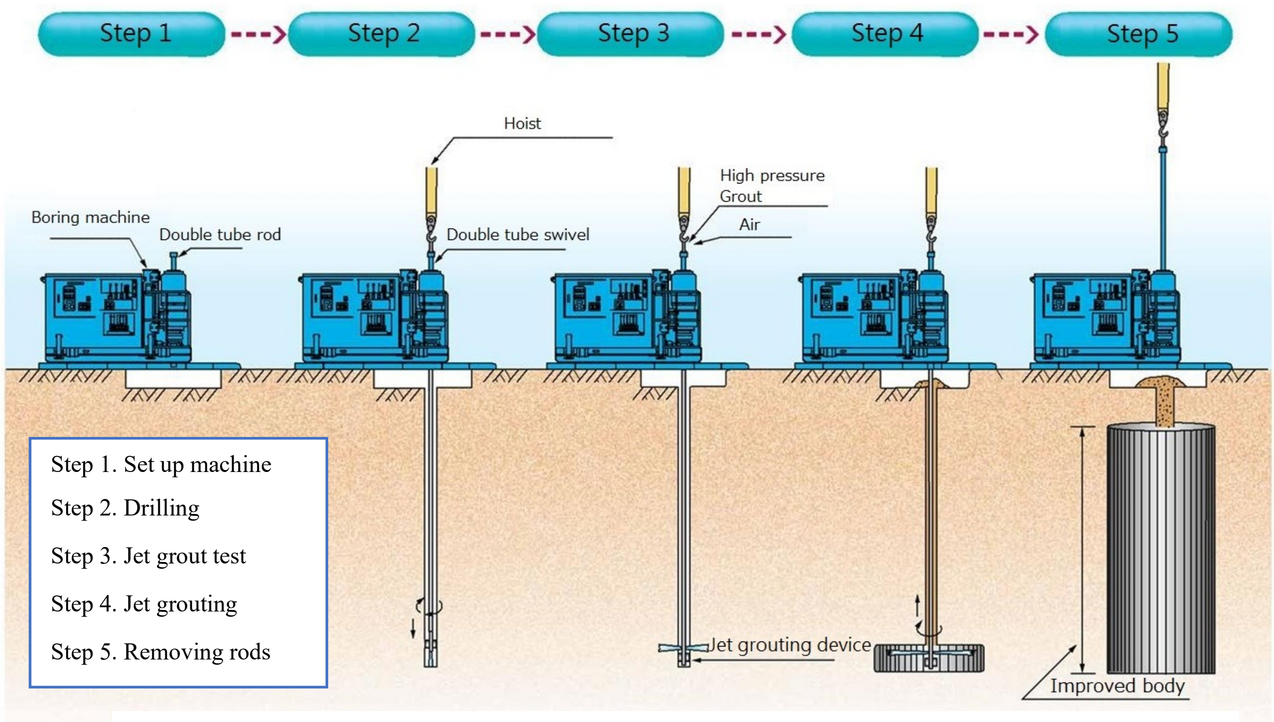

Figure 2 The typical construction procedure of jet grouting

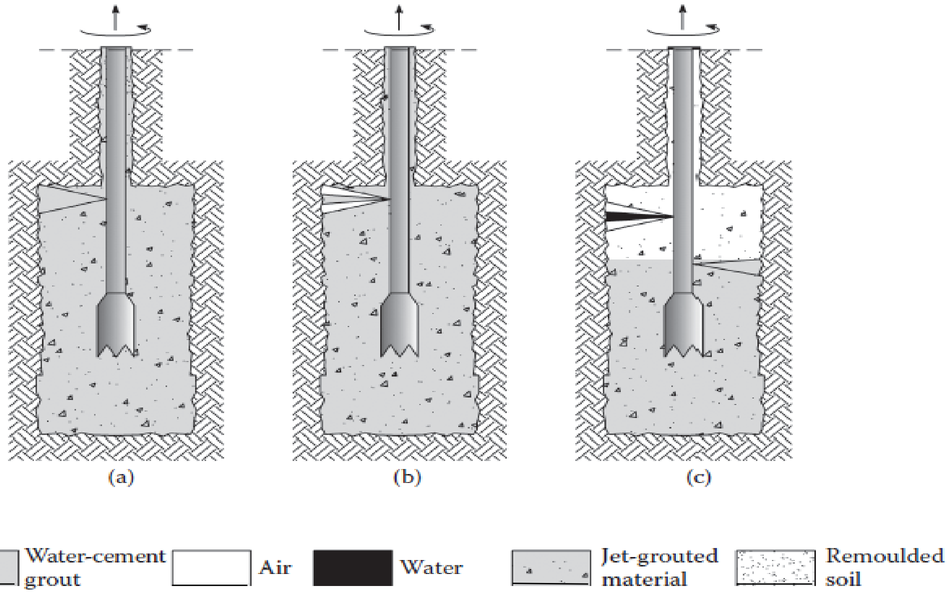

Figure 3 Typical jet grouting systems: (a) single fluid, (b) double fluid, and (c) triple fluid (Croce et al., 2014)

Until now, pioneers have devoted their efforts to developing an efficient system that can cut as long a distance as possible with a jet stream. Currently, it is possible to create improved bodies with very large diameters, and their behavior can be predicted with high reliability.

In the jet grouting improvement, it is necessary to consider the following two mechanisms:

- Transfer of high-pressure jet energy from the nozzle to the undisturbed ground.
- Interaction between high-pressure jet and soil.

In the initial stage of the ground improvement process, there is only a small space with a diameter slightly larger than the monitor created by the boring. Therefore, the distance between the nozzle and the untreated soil is relatively short. As the eroding progresses, the boundary between the ground and the fluid region moves outward, and the fluid region becomes larger. After reaching the undisturbed ground, a part of the jet fluid (q_1) eventually exchanges with soil particles to maintain a radial flow, while the remaining portion (q_2) mixes with the soil, flows through the rod, and moves toward the surface. Eventually, it is discharged onto the ground surface along with the excavated ground (refer to Figure 4).

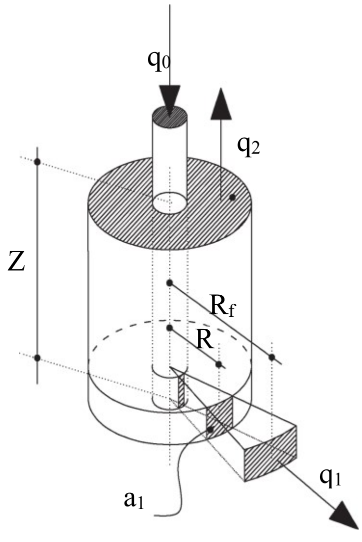

Figure 4 Radial flow and spoil return in jet grouting (Croce et al., 2014)

3.3 Experimental Study

Extensive research has been conducted by many researchers on the physical characteristics of jet streams in water, which form the basis of the performance of the jet grouting method. These studies have investigated the characteristics of jet streams, the distance they could reach, and the mechanisms of energy dissipation.

During the development stage of the method, the water jet stream tests were also conducted by the authors to compare and evaluate the performance in order to develop a more practical construction system with minimal energy loss. Full-scale ground injection experiments were also carried out simultaneously. The test contents, results, and overview of the basic performance considerations are introduced in the following sections.

In the water jet stream testing, the testing apparatus shown in Figure 5 is used to inject water and compress air from the nozzle of the front injection device into a water tank. The jet energy in water is measured as collision load acting on a circular target with a diameter of 10 cm, and the attenuation situation by distance is confirmed. The water jet stream testing program was carried out with 12 different injection sets including various injection pressures, nozzle diameters, and air injection amounts, using the monitoring system shown in Figure 5. The results of the water jet stream tests are presented in Figure 6. As shown in Figure 6, although there were differences in the collision loads for each set, a similar attenuation trend was observed. These values are invaluable to the development of the jet grouting technique. The results shown in Figure 6 were used to improve the jet grouting device by reducing the attenuation of the collision load. Currently, the water jet stream testing is used for the

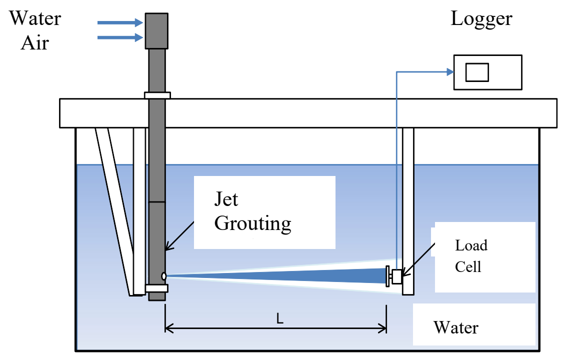

Figure 5 Underwater jet stream test with the monitoring (Shinsaka et al., 2018)

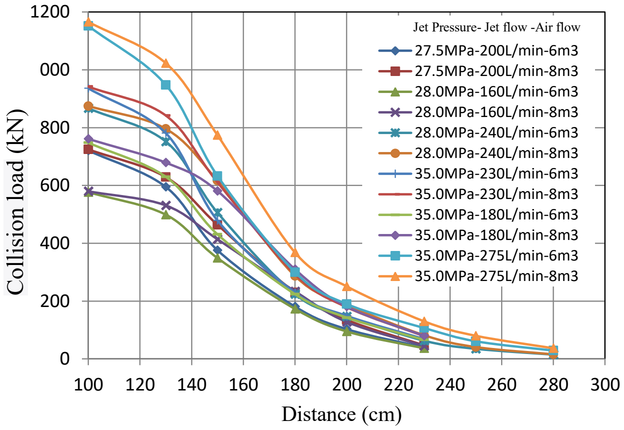

Figure 6 Results of underwater jet tests

quality control of the jet grouting device. The performance of the jet grouting device is confirmed before shipping and after maintenance using the testing apparatus.

Different injection sets were constructed in a full-scale ground injection experiment to confirm the shape and quality of the improved body (Photo 1). The results of the full-scale ground injection test were used to evaluate the relationship between the energy considerations of the jet stream in water and the shape (construction diameter) of the improved body.

Photo 1 Excavated jet grouting (Shinsaka et al., 2013)

According to previous research, the shape of the improved bodies, i.e. the distance of ground eroding by high-pressure injection (S), is influenced by the injection pressure (P_m), nozzle diameter (injection amount) (d_0), jet lifting velocity (V_{tr}), repetition frequency (eroding times) (N), and the strength of the ground (σ_c), and can be expressed by the following equation.

$$S = f(P_m, d_0, V_{tr}, N, \sigma_c) \tag{1}$$

According to independent research, it was found that in addition to the above factors, there is also a significant correlation between the distance of ground eroding by high-pressure injection (S) and the amount of air injection Q_e. Through our own research, it has been confirmed that there is a strong correlation with the air injection amount Q_e (Yamazaki et al., 2012). The results of our study on the relationship between injection cases and the shape of the improved body in full-scale ground injection experiments are presented below.

Table 1 shows the values of each of the above parameters in four experimental cases (injection cases A to D). Table 1 also shows the the SPT-N values of the improved ground strength for the upper part of the improved body (fine sand) and the lower part of the improved body (gravel). The moving speed shown in Table 1 refers to the moving speed of the jet grouting along the outer boundary of the column with an average diameter. The eroding times refer to the times of grouting on the point of the arc. The ground eroding distance refers to the average value of the distances measured from the column center to the column edges.

Table 1 Parameters for full-scale test (Shinsaka et al., 2013)

Case		A	B	C	D
SPT-N	Upper part (Clayey sand)	10	10	10	10
	Lower part (Gravel)	30	30	30	30
Injection pressure P_m (MPa)		37	35	37	35
Nozzle diameter d_0 (cm)		0.39	0.44	0.44	0.44
Air flow rate Q_e (Nm^3/min)		5.0	7.0	6.5	7.0
Moving speed V_{tr} (cm/sec)		73.9	102.6	119.1	97.4
Eroding times (N)		2.6	1.5	2.5	3.2
Eroding distance S_o (cm)	Upper part (Clayey sand)	170	189	227	236
	Lower part (Gravel)	190	208	229	229
	Average	178	196	228	233

(i) Cases B ~ D were carried out by the same parameters of the grout pressure P_m, nozzle diameter d_0, and air pressure Q_e and different grouting moving speed V_{tr} and eroding times N. Correlation between the eroding times N and the ground eroding distance S_0 is shown in Figure 7. Additionally, Figure 8 shows the relationship between a parameter S as a function of the moving speed, V_{tr} and the eroding times, N and the measured ground eroding distance S_0. The parameter S was obtained assuming the relationship $S = a\,V_{tr}^{\,b}\,N^c$ with the coefficient values of a, b, and c shown in Equation (2).

$$S = 200 V_{tr}^{-0.025} N^{0.233} \tag{2}$$

This correlation shown in Figure 8 indicates that the ground eroding reaches a longer distance as the eroding times increases. As a reference, 10% of the grou nd eroding distance will increase if the eroding times increase from 2 times to 3 times. While moving speed in the range of this time (V_{tr} = 95 ~ 120 cm/s) does not have a significant influence on the ground eroding distance.

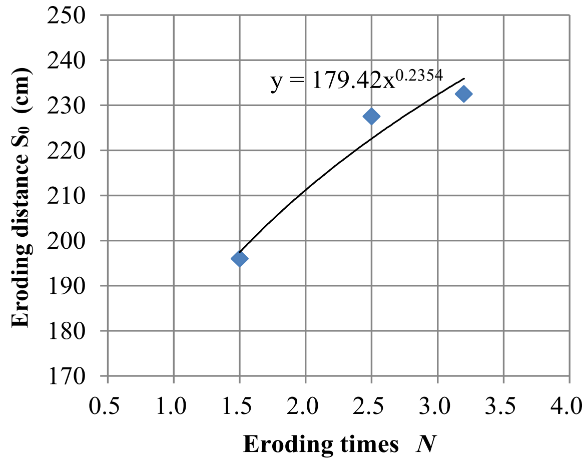

Figure 7 Correlation between eroding times and eroding distance (Shinsaka et al., 2013)

(ii) The relationship between a parameter X as a function of the jet pressure P_m, nozzle diameter d_0, and air jet flow Q_e, and the distance Y achieved by the energy required for the ground cutting obtained from the underwater jet test is shown in Figure 9. The parameter X was obtained assuming the relationship $X = P_m^{\,a} \cdot d_0^{\,b} \cdot Q_e^{\,c}$ with the coefficient values of a, b, and c shown in Equation (3). The energy required for ground cutting was set based on the comparison with the actual shape full-scale experiment.

$$Y = 77.5P_m^{0.271}\ d_0^{0.325}Q_e^{0.190} \tag{3}$$

In the formula, the nozzle diameter d_0, which is equivalent to the injection volume, has the greatest influence on the reaching distance Y.

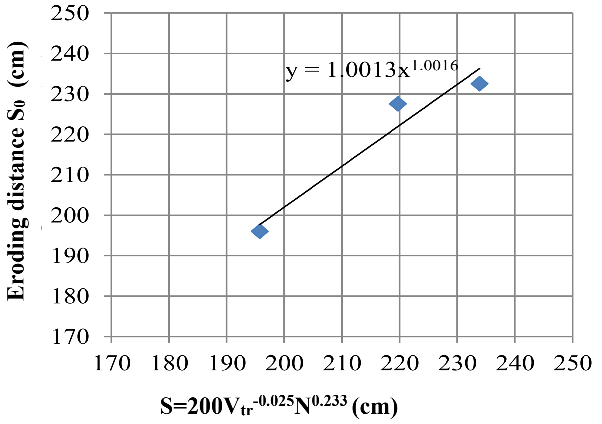

Figure 8 Correlation between moving speed and eroding distance (Shinsaka et al., 2013)

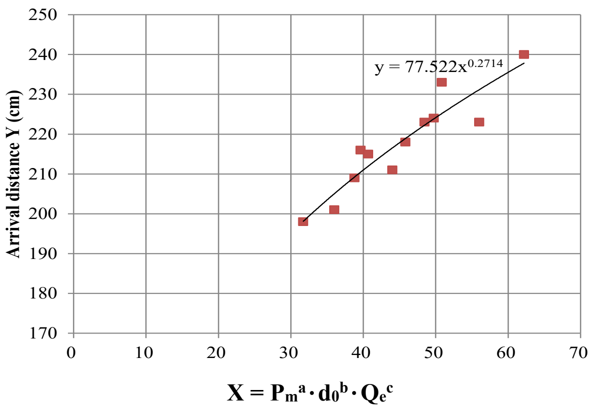

Figure 9 Evaluation of eroding distance based on performance function on jet grouting device (Shinsaka et al., 2013)

(iii) Based on the relationships expressed in Equations (2) and (3), the relationship between the soil eroding distance and each parameter was established in Equation (4). It should be noted that Equation (4) is valid only for sandy soil with SPT-N = 10 to 30. In addition, each parameter is limited to the applicable range shown in Equation (4) based on the parameter values used in the full-scale experiments.

$$S = 64.0P_m^{0.271}\ d_0^{0.325}Q_e^{0.190}N^{0.233}V_{tr}^{-0.025} \tag{4}$$

Where:

S = soil eroding distance (cm)
P_m = jet injection pressure (MPa) ($35 \leq P_m < 40$)
d_0 = nozzle diameter (cm) ($0.35 \leq d_0 < 0.45$)
Q_e = air injection volume (Nm^3/min) ($5.0 \leq Q_e < 7.0$)
V_{tr} = moving speed (cm/s) ($95 \leq V_{tr} < 120$)
N = eroding times ($1.5 \leq N < 3.5$)

Figure 10 shows the comparison of the estimated eroding distance to the actual eroding distance obtained from the full-scale ground injection experiment. Even though there is some variation since each plot is an individual measured eroding distance value, a general correlation can be observed in Figure 10. Therefore, it was concluded that the ground excavation distance in the jet grouting is greatly influenced by the construction system, including jetting pressure, nozzle diameter (injection volume), air injection volume, and jetting time (moving speed and eroding times).

Through the above research, the authors confirmed the correlation between the improved body shape (ground eroding distance) proposed in the previous research and the generated jet flow factor and verified its applicability. However, this evaluation was conducted under specific individual monitors and limited conditions. Hopefully, the results of this study can serve as an important reference for future research and development.

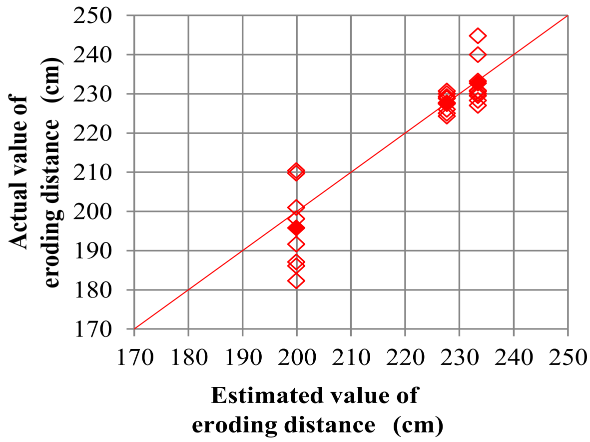

Figure 10 Correlation between actual and estimated eroding distance (Shinsaka et al., 2013)

4. CHALLENGES AND EFFORTS IN DEVELOPING NEW METHODS FOR JET GROUTING

4.1 Challenges in Jet Grouting

Jet grouting has evolved over several decades and has been used to achieve unparalleled results, which are attributed to the following features:

- Ability to create large improved solidified cement bodies in the ground by creating small holes in the soil with a minimal impact on the surrounding soil.
- Ability to create continuous improvements of various shapes and sizes with excellent mechanical properties and very low permeability.

These features increase the bearing capacity of new and existing foundations, reduce the amount of subsidence, prevent ground collapse during excavation, prevent fluid storage for pollution prevention, and stop water for underground water cutoff. It is possible to use the jet grouting technique to solve various ground problems. It is also possible to work in confined spaces or places that are difficult to reach by other means. Even under difficult working conditions, it is possible to improve the ground using relatively lightweight equipment.

Although the jet grouting method has already been widely used, there are still many problems to be solved in order to further improve its value as a ground improvement method. These included issues related to improving workability to shorten the construction period and reduce construction costs, issues related to the quality of improved structures, issues related to reducing environmental impact, and issues related to expanding the scope of application.

Figure 11 shows a summary of the challenges of the jet grouting method and the achievement that can be obtained by solving those challenges. In the figure, for example, if the "high-speed execution" becomes possible, the "shortening of construction period", "reduction of cement", and "reduction of industrial waste" could be possible. As a result, the "reduction of construction costs" and "reduction of environmental load" can be realized.

4.2 Practical Application and 12-Year History of the V-JET Method

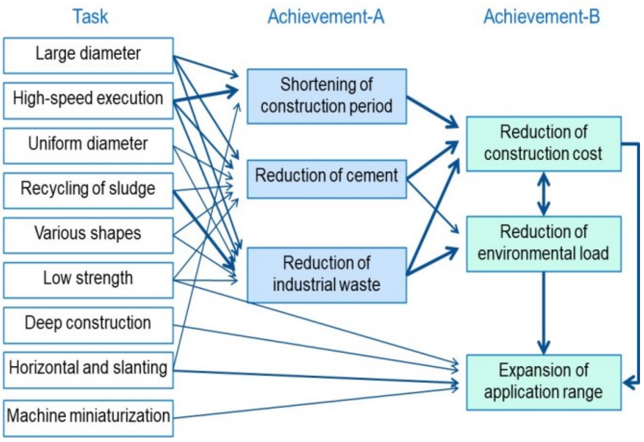

Figure 11 Issues of jet grouting method

In 2011, the authors repeated the full-scale construction experiments and achieved the practical application of a new jet grouting method called "V-JET method". The V-JET method was developed with the aim of increasing the diameter and increasing the construction speed in response to many challenges faced by the jet grouting method at the time. After establishing the specifications and conducting a full-scale construction test, the system was implemented in practical applications in 2011. The objectives of achieving "larger diameter" and "acceleration of construction" represent the progressive advancements in the ultra-high pressure grout pump, which is the core component of the construction machinery. Additionally, these goals aid to minimize energy loss during grouting, facilitating efficient ground cutting and mixing stirring in a short time. These objectives are attainable through the utilization of advanced injection equipment and implementation of construction specifications derived from extensive experience and analysis of experimental data.

The construction system of the V-JET method is classified as a double-fluid method where high-pressure injection of hardener slurry and compressed air is utilized. Three construction specifications, namely V1, V2, and V3, which combine mechanical equipment according to the improved body diameter classification (2.0 m, 3.5 m, 5.0 m) were prepared. Additionally, to address ground improvement needs such as liquefaction countermeasures, three types of VE specifications have been developed. These specifications feature significantly reduced injection amounts (hardening material amounts) per improved volume, tailored to meet the required level of improvement strength as per the design requirements.

The implementation results of the V-JET method have been steadily growing, and as of the end of September 2022, there have been 385 construction cases and a total improved volume of 911,000 cubic meters in Japan. As a technical evaluation of the method, it has been registered by government agencies in Japan and evaluated by technical evaluation institutions. In 2017, the standard mixture of hardening materials was reviewed to achieve further acceleration of construction and reduction of sludge discharge. Furthermore, in 2019, the V0 type with a more compact construction system was added, and the construction specifications were reorganized into four types. The current standard specifications are shown in Table 2.

Over the course of the past 12 years, there have been notable advancements in drilling and excavation machinery, as well as construction management equipment. With the expansion of the application range of the jet grouting method, there is an increasing need for construction in narrower spaces. In response to this demand, small drilling and preparation machines have been manufactured. For example, in the ground improvement work for the excavation base of an operating subway station expansion project, a small machine (Photo 2) weighing 900 kg and standing at a height of 1.7 m was newly manufactured for construction on the tracks inside the station.

Table 2 Standard design parameters

Type		V0		V1		V2		V3			
Grout Pressure	(MPa)	35		35		35		35			
Grout Flow Rate	(L/min)	160		240		360		540			
Effective Column Diameter	(m)	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
Lift Rate	(min/m)	4	7	7	10	9	12	10	12	15	18
Rotation	(rpm)	10-20	6-12	6-12	4-8	5-9	4-7	4-8	4-7	3-5	3-5

※ Effective column diameter is for sandy soil (N ≦ 50), clayey soil (N ≦ 3), and as columns not more than 30m deep.

The machine was manufactured, and its transportation to the construction site involved a manual process of moving it a yard located 250 meters away, once the daily business operations were finished. This small machine was also used for the seismic reinforcement of important cultural heritage buildings, where construction activities needed to be performed within the confines of the buildings. Additionally, in recent years, there has been a focus on improving workability, especially for efficient construction in oblique settings. To address this, a crawler-type drilling machine (Photo 3) equipped with a 7-meter-long leader has been employed.

Photo 2 Construction inside subway station with a small machine

Photo 3 Construction with a crawler type drilling machine

In terms of construction management technology, in addition to the main unit, a construction management device that can be checked on a tablet terminal has been developed and put into practical use. This makes it possible to check and manage construction data in real-time, such as the inclination angle of construction machinery, construction depth, hardener injection pressure and flow rate, compressed air pressure and flow rate, injection equipment rotation speed, and lifting speed. The measured data is recorded and saved in the main unit of the management device, facilitating effortless output generation such as table creation and drawing (Photo 4).

Photo 4 Construction monitoring device

In addition, the JWM System (Jet Wave Monitoring System) has been developed and implemented as a cutting-edge technology to monitor real-time progress of the improved body, ensuring the quality and effectiveness of the ground improvement efforts. The JWM system estimates the improvement diameter at each depth by measuring and quantifying the change in the sound of the cutting flow impinging on a measuring tube pre-installed within the subsurface improvement. It is a construction management technique. The configuration of the JWM measurement system is shown in Figure 12. Prior to construction, multiple measuring tubes are installed at different distances from the center of the improved pile before construction. During the construction process, the time-series changes in the volume of the jet stream that crosses each measuring tube are measured and plotted into a graph, as shown in Figure 13. When the jet flow reaches the measurement tube, the changes in the measurement data become a regularly spaced mountain-shaped linear graph, as shown in Figure 14. The size of the mountain shown in Figure 14 is proportional to the strength of the jet flow. An analysis is performed by evaluating the size of these mountains, and it is now possible to estimate the improvement diameter of the created soil layer for each depth using dedicated analysis software. Currently, it is possible to estimate the improvement diameter for each depth by using dedicated analysis software. This technology is mainly used in a trial test before construction or in the initial stage of construction. This technology has been used to confirm the improvement status of the improved body in more than 50 construction projects so far.

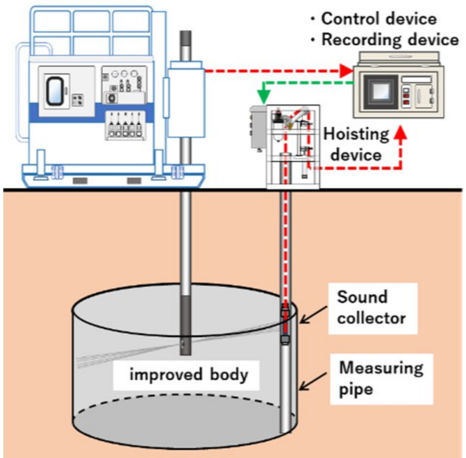

Figure 12 Configuration of the JWM system

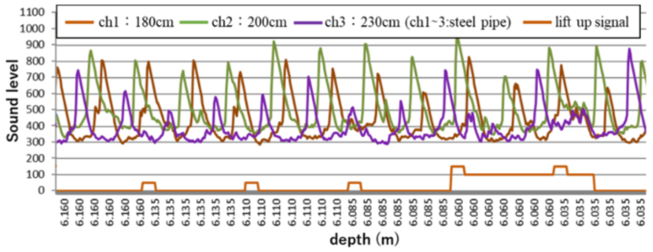

Figure 13 Measurement data of JWM System

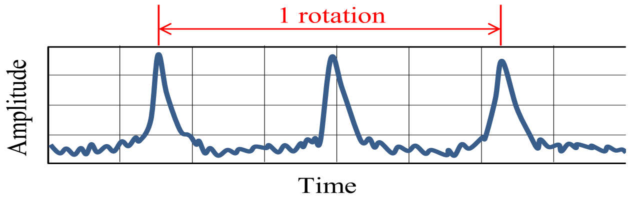

Figure 14 Amplitude pattern (model) (Shinsaka et al., 2013)

A practical application technology known as the Multi-Fan Method was developed to efficiently construct wall-like improvement bodies and was put into practical use in 2016. The improvement body of the Multi-Fan method has a multi-fan cross-section composed of fans of different diameters, as shown in Figure 15. A construction machine with a rotating control function of the front injection device is used to control the rotation angle and rotation cycle. The standard shape of the improvement body and the improvement body excavated after construction are shown in Figure 15.

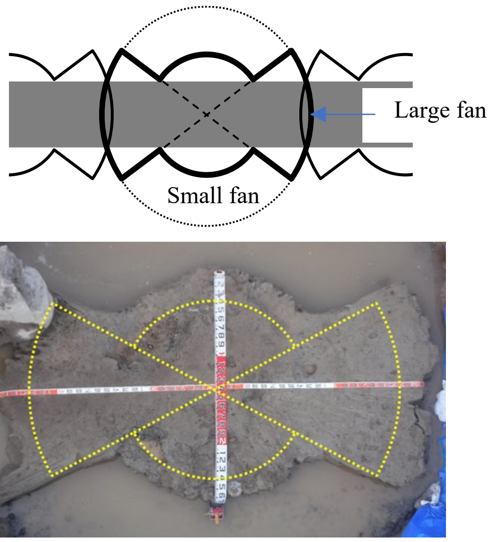

Figure 15 Multi-fan improved body (Shinsaka et al., 2017)

Regarding the global expansion of the V-JET method, active efforts have been made in the Southeast Asian region and Europe (Photo 5). In 2012, the company initiated construction projects in Hong Kong, and since then, notable accomplishments have been achieved in various locations, including Taiwan, Taipei (Photo 6), Malaysia, Singapore, and Thailand (Photo 7). In addition, in 2015, a license agreement was signed with a construction company in Austria, resulting in the accumulation of successful construction achievements across European countries, primarily Germany and Austria. The construction volume by this construction company in Europe is increasing yearly from 2017 to 2022. A total of 106 construction projects with a total improvement volume of 256,000 m^3 have been carried out for various purposes, such as the improvement of excavation bottoms, underground beams, underpinning, and cutoff walls.

Photo 5 Construction in Europe

In the Southeast Asian region, the Rapidjet construction method is being developed by applying the knowledge and technology of the V-JET method to improve operability (Wong et al., 2019; Cheng et al., 2019; Fuzawa et al., 2020; Wong et al., 2022; Shakya et al., 2023). Currently, it is used as an auxiliary construction method for shield construction, such as ground improvement for excavated bottoms, preceding underground beams, and shield launching and arrival protection in subway construction in Bangkok (Chao et al., 2019; Subhasinghe et al., 2020; Silva et al., 2020; Li et al., 2022; Cheng et al., 2023). For example, MRTA Blue Line Extension Project in Thailand and MRTA Orange Line East Project in Thailand as mentioned in the following sub-sections. The construction results in Thailand until 2022 amounted to a total improvement volume of 21,210 cubic meters.

Photo 6 Construction in Taipei, Taiwan

Photo 7 Construction in Thailand

4.2.1 Case Study of the MRTA Blue Line Extension Project

4.2.1.1 Site Conditions

For the MRTA Blue Line Extension Project, the TBM retrieval shaft is located at the Northern end of the Sanam Chai (BS12) Station, which is the extension of Chaloem Ratchamongkhon (or the Blue Line) of the Bangkok MRT. The Blue Line Extension Project is 16.51 m long, 9.60 m wide, and 32.5 m deep. The subsoil conditions at the site are shown in Figure 16. The groundwater level was measured at a depth of 10 m below the ground surface. As indicated in Figure 16, the site has mostly soft clay to stiff clay and sand interlayers. A soft clay layer is located within the upper 10 m. The 1st stiff clay layer is located at depths of 10 to 25 m. The 1st sand layer is located at depths of 25 to 35 m. The 1st sand layer has the SPT-N values of about 20 to 35 and a fine content of ≈ 0 to 10%. The 2nd stiff clay layer is located at depths of 35 to 38 m. The 2nd stiff clay layer has the SPT-N values of about 20 to 60 and a fine content of approximately 70%. The 2nd sand layer is located below a depth of 38 m and is more than 20 m thick. Hence, when excavating to the designed depth, the impermeable 2nd stiff clay layer (only 0 ~ 4 m thick) is unable to resist the artesian water pressure from the permeable 2nd sand layer and might cause the risk of uplift and piping in the 2nd stiff clay layer (refer to Figure 17).

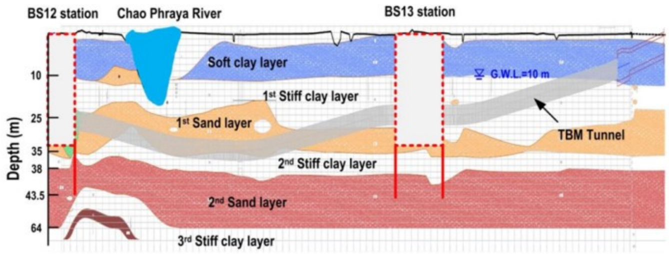

Figure 16 Soil profile and the locations of BS12 station and the TBM retrieval shaft

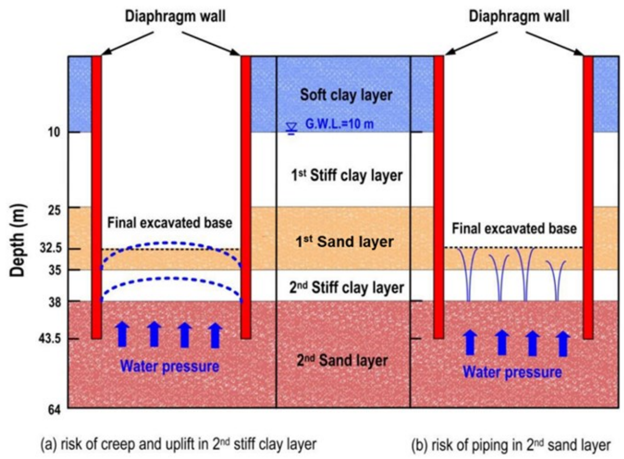

Figure 17 Construction risk of the retrieval shaft and the purposed jet grouting (Cheng, et al., 2015)

When excavating an extremely deep ground and the groundwater level is relatively high, the thickness of the impermeable layer under excavation base is the key factor that influences the safety of construction. In order to improve construction safety, base seal grouting, as a compensation measure, is applied to increase the thickness of the impermeable layer and to improve the strength and water tightness of excavation base. This can also reduce the uplift pressure from the artesian water.

4.2.1.2 Jet Grouting at the Base of the Excavation

Jet grouting was conducted at the base of the excavation to prevent the risk of uplift and piping in the relatively thin 2nd stiff clay layer. Figure 18 shows the grouting plan and cross-section view of the jet grouting dimensions. A total of 30 JGP columns with a diameter of 3.2 m were installed at the site. The grouting thickness was about 9.86 m and the depth of drilling was 43.81 m below the ground surface. The grouting parameters are provided as follows: grout pressure = 35 MPa; grout flow = 360 L/min; withdraw rate = 14 min/m; and rod rotation = 4 rpm. The water-cement ratio is 758 kg (water) : 750 kg (cement).

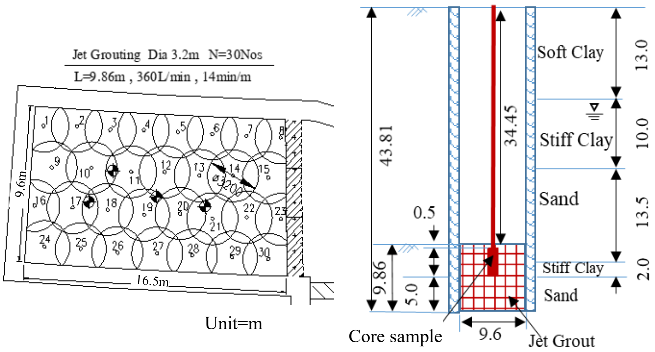

Figure 18 Jet grouting layout and cross-section

4.2.1.3 Quality Control

Four verticality tests were carried out to check the verticality. The results of the verticality tests indicate that the verticality was less than 1/250 at a depth of 44 m. One coring test was conducted at the intersection of grout points 4, 5, and 12. The unconfined compression strengths for the cored samples were measured to be on an average of 6 MPa, which met the design requirement strength of 3.0 MPa. A field pumping test was carried out, and the results of the pumping test showed that there was no water in the retrieval shaft. The required hydraulic conductivity of the sandy layer was 5×10^{-5} cm/sec after grouting. Figure 19 shows that the base of the excavation was in a dry condition after grouting. Consequently, the design requirement for hydraulic conductivity was met for the MRT underground retrieval shaft.

Figure 19 Final excavation base at a depth of 32.5 m for TBM shaft

4.2.2 Case Study of the MRTA Orange Line East Project in Thailand

4.2.2.1 Site Conditions

The Pradit Manutham Station (OR15) is an underground station along the MRTA Orange Line East (Contract E1) Project, which consists of 3 underground stations (OR13: Thailand Cultural Center, OR14 MRTA, and OR15: Pradit Manutham). The portion of this project is approximately 6.3 km in length. The area under consideration lies within relatively flat terrain where the ground level varies from 100.0 to 102.0 mRL. The location of the MRTA Orange Line East Project is presented in Figure 20. Along the MRTA Orange Line East Project, the OR15 Station is considered to have a high-risk potential to the nearby Sirat Expressway (Maung et al., 2019). Therefore, the OR15 Station was chosen for the jet grouting application. The plan view of the OR15 Station and the Sirat expressway is presented in Figure 21.

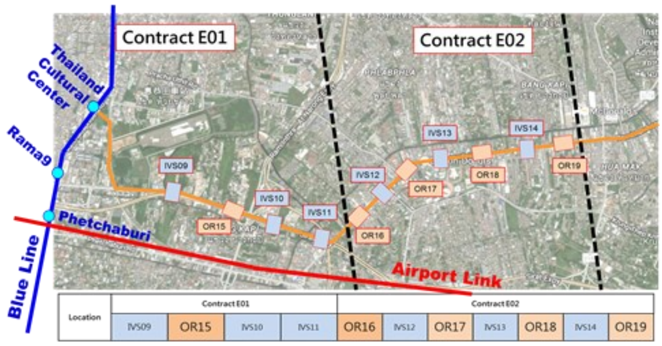

Figure 20 MRTA Orange Line (Contract E1) Project

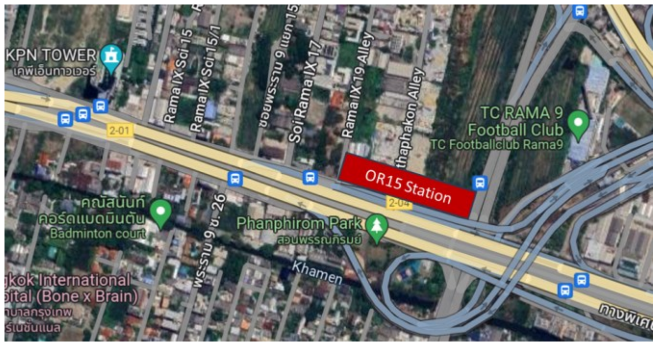

Figure 21 Plan view of OR15 station and Sirat expressway

Without any protection measures for the Sirat Expressway viaduct, it was estimated that the deflection at the base slab of the diaphragm wall could increase up to 66 mm with an unsatisfied estimated moment in the piles. To avoid the excessive amount of deflection, it was determined to install 2 preceding beams with a thickness of 3.0 m using the large diameter jet grouting technique. The first preceding beam is constructed at a depth of 10.35 m below the ground level in a medium clay layer. The second preceding beam was installed in a sand layer, which is at a depth of 26.0 m below the ground surface. The layout plan and cross-section of the preceding beams at the OR15 Station are shown in Figure 22 and Figure 23. A total of 110 points of the jet grouted piles as shown in Table 3 were constructed.

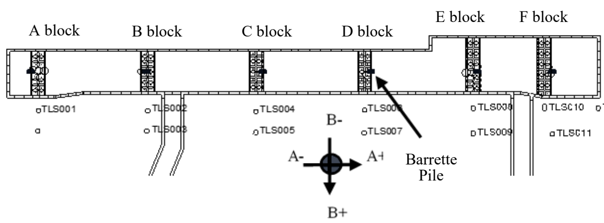

Figure 22 Layout plan of preceding beams and instrumentation plan at OR15 station

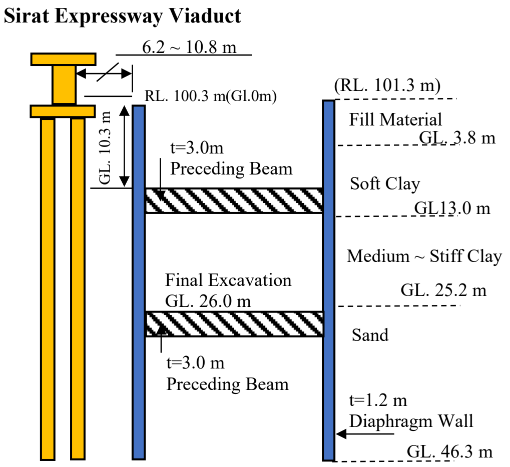

Figure 23 Cross-section of preceding beams at OR15 station

Table 3 Quantity of preceding beams at OR15 station

Block / JGP	JGP Quantity, Pts					
	A	B	C	D	E	F
φ = 3.5m	16	16	16	16	21	22
φ = 2.5m	1	1				1

4.2.2.2 Jet Grouting for Preceding Beams

The Rapid-Jet Method was used to form the preceding beams at the site. Figure 24 shows the design plan of the jet grouted preceding beam (Block F). Figure 24 indicates that the designed width of the preceding beam within the grout treated zone ranges from 5 to 6 m. A larger nozzle diameter of 4.2 mm was used to allow a larger grouting rate. The grouting parameters used at the site are provided as follows: grouting pressure = 30 ~ 34 MPa, grouting rate = 360 L/min, rod rotation = 4 rpm, and withdrawal rate = 10 ~ 12 min/m. The grouting parameters allowed the contractor to rapidly install grouting piles with a diameter up to approximately 3.0 m at a depth of up to 50 m below the ground surface.

4.2.2.3 Quality Control

A) Electrical resistivity testing

An electrical resistivity testing was adopted to verify the constructed width of the preceding beam with the jet grouted piles installed in the medium clay layer underneath the OR15 Station. The electrical resistivity testing was conducted at Block F of the station, as shown in Figure 22. The testing was conducted with probes spaced at a distance of 18.8 m across the beam.

To determine the resistivity values of the grout treated and untreated soils, the resistivity test was conducted in the laboratory for soil samples obtained from the site. The resistivity values of the untreated clay samples were determined to range from 1.5 to 1.6 Ohm-m. The resistivity values of the grout treated clay samples were determined to range from 7.0 to 30.0 Ohm-m. The resistivity value for the transition zone between the completely treated clay and untreated clay was assumed to be 4.25 Ohm-m, which is the average value of the resistivity values for the samples of the grout treated clay and the untreated clay. The resistivity value of 4.25 Ohm-m was used to determine the effective diameter of the jet grouting.

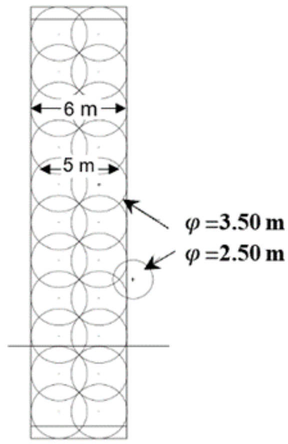

Figure 24 Design plan of the jet grouted preceding beam (Block F)

The results of the electrical resistivity test performed at Block F are shown in Figure 25. Figure 25 indicates that the measured resistivity values for the entire cross-section range from 0.6 to 22 Ohm-m. Using the resistivity value of 4.25 Ohm-m for the transition zone, the constructed width of the preceding beam was estimated to be approximately 6.4 m. Field observation was conducted to measure the constructed width of the preceding beam when the preceding was exposed. The constructed width of the beam was measured to range from 5.8 to 6.3 m. The visual observation confirmed the estimated width of the beam obtained from the resistivity test. Therefore, it is concluded that the constructed preceding beam meets the requirement of the designed width.

B) JGP coring test results

The completion of the jet grouted piles is based on the compliance that the unconfined compression strength (UCS) of the cement-treated soil columns shall reach a minimum value of 1.2 MPa for clayey layer and 2.0 MPa for sandy soil layer. Total 3 coring points were carried out in the preceding beams of Blocks A, D, and F, as shown in Figure 26. The average values of UCS, E_{50}, unit weight, and water content of the soft clay core samples are 2.15 MPa, 172 MPa, 14.7 kN/m^3, and 41.65%, respectively. The average values of UCS, E_{50}, unit weight, and water content of the sand core samples are 7.53 MPa, 286 MPa, 18.5 kN/m^3, and 14.47%, respectively. The average value of TCR is more than 95% for Blocks A, D, and F. The relationship between UCS vs. E_{50} for the soft clay and sand are shown in Figures 27 and 28, respectively. Figures 27 and 28 show that the modulus/strength ratio increases with strength, and $E_{50} = 80.0q_u$ and $E_{50} = 38.1q_u$ for the soft clay and sand, respectively. Figures 29 and 30 show the relationship between UCS and E_{50} vs. unit weight for the soft clay and sand, respectively. Figures 29 and 30 indicate that the UCS/γ_t and E_{50}/γ_t ratios increase with the unit weight of the core samples.

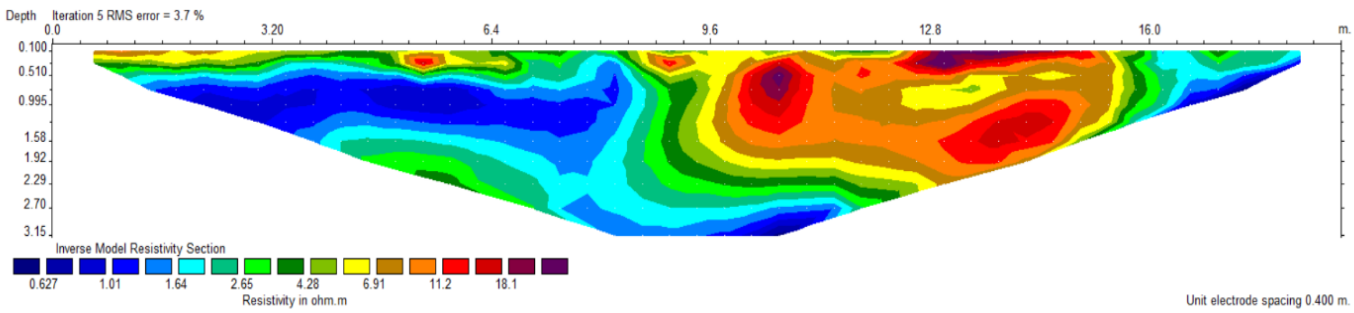

Figure 25 Results of electrical resistivity test for Block F

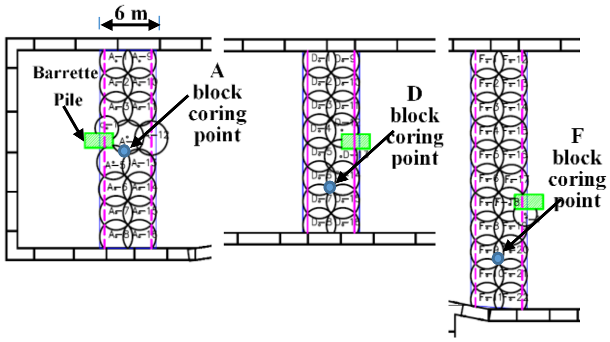

Figure 26 Coring points at the preceding beams

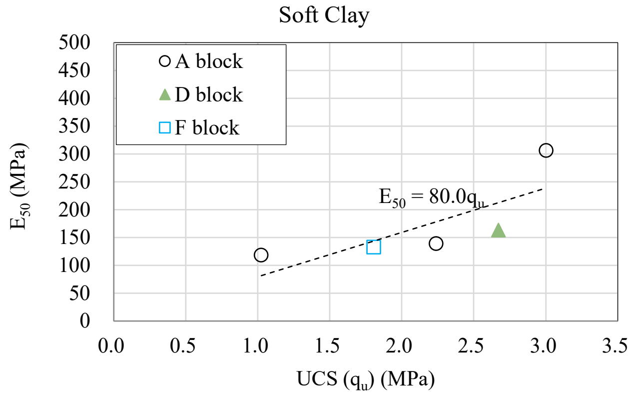

Figure 27 Relationship between E_{50} vs. UCS for soft clay

4.2.2.4 Monitoring Results for Sirat Expressway

Twelve tilt sensors TLS001 to TLS0012 were installed on the piles of the Sirat Expressway to monitor the tilting of the piles during construction. The tilt sensors layout plan and tilt directions A & B of the tilt sensors are shown in Figure 22. The tilt direction A of the tilt sensors is parallel to the OR15 Station and the tilt direction B is perpendicular to the station. The tilt sensors were installed in June 2018. The initial readings were taken in June 2018 and continue monitoring by a real time system was conducted afterward. The action, alarm, and alert (AAA) response values of highway structures adopted for this project are shown in Table 4. The monitoring results of the tilt sensors are presented in Table 5. It was observed that the maximum tilt of the tilt sensor TLS001 at direction B was measured to be 1/901, which is greater than the alert limit of 1/1000, but less than the alarm limit of 1/769. The maximum tilt of the tilt sensor TLS0012 at direction B was measured to be 1/556, which is greater than the alarm limit of 1/769, but less than the action limit of 1/500. The tilting measured at TLS0012 does not seem to be caused by the excavation work, because TLS0012 is located at the corner of the station. Consequently, except for the 2 points mentioned above, the values of tilting at the monitoring points are all less than the alert limit of 1/1000.

Table 4 AAA Response values of highway structures

Action Limit	1/500	0.0020 Rad
Alarm Limit	1/769	0.0013 Rad
Alert Limit	1/1000	0.0010 Rad

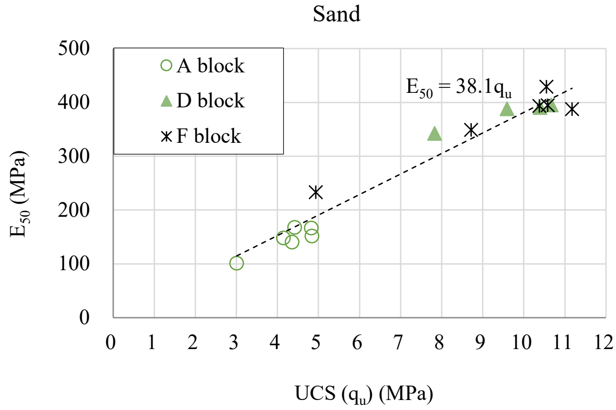

Figure 28 Relationship between E_{50} vs. UCS for sand

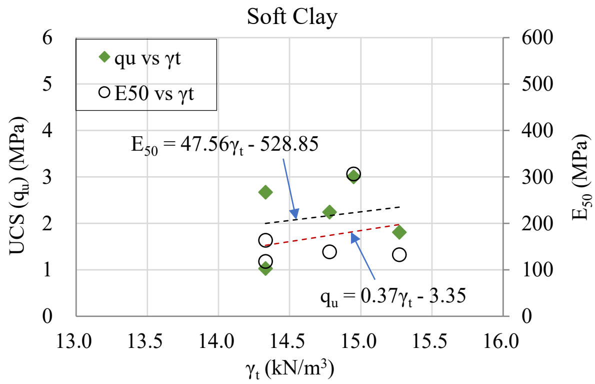

Figure 29 Relationship between UCS, E_{50} vs. γ_t for soft clay

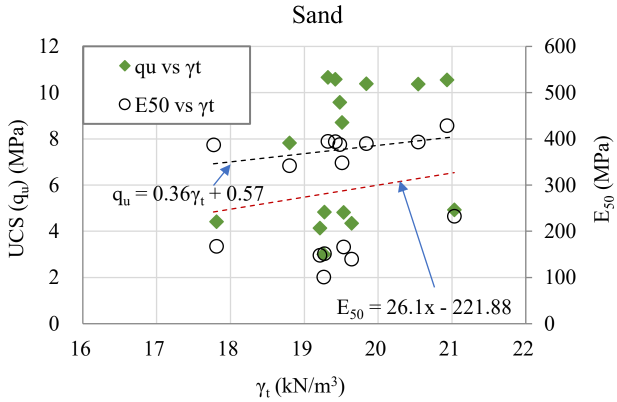

Figure 30 Relationship between UCS, E_{50} vs. γ_t for sand

4.3 Technological Challenges for 2030

Looking ahead to 2030, seven years from now, what technological challenges lie ahead of us? First of all, there are "labor-saving and automation of construction" and "visualization of product quality improvement". In Japan, labor-saving and automation of construction have become a challenge for the entire construction industry, and efforts have already begun in the field of ground improvement. In the case of automated construction using the jet grouting method, it is desirable to possess a system capable of real-time monitoring and feedback that comprehends the specific attributes of the target ground and the ongoing construction conditions. Achieving this would enable partial systematization of the "judgment" process, which previously relied solely on skilled workers. Furthermore, efforts towards labor-saving and automation that involve the accumulation and analysis of construction data will also lead to the visualization of the construction process and improved quality.

Table 5 Monitoring results of tilt sensors

Tilt Sensor	Pile	Jet Grout Block	Maximum Tilt (Rad)	
			Direction A	**Direction B**
TLS001	P490-3	Block A	<1/1000	-1/901
TLS002	P490-4-L	Block B	+1/1111	+1/1111
TLS003	P490-4-R		+1/2500	+1/3333
TLS004	P490-5-L	Block C	<±1/2500	<±1/2500
TLS005	P490-5-R		< ±1/3333	< ±1/1667
TLS006	P490-6-L	Block D	< ±1/5000	-1/1000
TLS007	P490-6-R		+1/2500	-1/1111
TLS008	P490-7-L	Block E	+1/1667	-1/1667
TLS009	P490-7-R		+1/1667	-1/1667
TLS010	P492-1	Block F	<±1/2500	-1/1250
TLS011	P490-8		+1/2500	-1/1250
TLS012	RM5-0+130.8	Corner of Station	< ±1/1667	-1/556

Visualizing product quality improvement will significantly change the conventional quality management methods that have predominantly relied on post-construction surveys. If it becomes feasible to grasp the size and strength characteristics of the improved structure in real time during construction, it will have a significant impact on design and construction management methodologies. This advancement will not only enhance productivity but also broaden the scope of applications.

Reducing and reusing sludge will emerge as a significant technological endeavor to mitigate the environmental impact in the future. In the jet grouting method, a large amount of sludge discharged poses significant drawbacks in terms of construction costs and environmental impact, yet no effective solution has been proposed. Future initiatives aimed at resolving this issue are eagerly anticipated.

5. CONCLUSIONS

The history of the development of the jet grouting method and the basic improvement mechanisms of the method that have been focused on have been discussed. Additionally, an overview of the technical aspects of the development of new methods and prospects has been provided in the paper.

The jet grouting method is a technology with great potential in the field of ground improvement, and it is convinced that this technology will continue to be widely used around the world. Furthermore, it is strongly believed that there is still plenty of room for further technical advancements in this field. As discussed in the previous sections, further technical advancements in the field of jet grouting may include improvements in the efficiency and effectiveness of the grouting process, development of more precise and accurate monitoring systems, and enhancement of equipment and machinery for increased productivity and versatility. Additionally, advancements in automation and digitization, such as real-time data analysis and feedback systems, could revolutionize the construction and management of jet grouting projects.

For the jet grouting method to continue to develop in the future, many researchers need to be involved in its development. In addition, many construction workers must be involved and expand the technology. A basic understanding of improvement mechanisms and the accumulation of practical experience are prerequisites for engineers to acquire advanced construction technology. It is also an important task to deepen collaboration with measurement technology and machinery technology and to construct a construction system that enables labor saving and automation. It is my sincere hope to be able to contribute to this great development trend.

Finally, my heartfelt gratitude is extended to all those who have contributed to the development of the jet grouting method, including the esteemed senior colleagues who have played pivotal roles.

6. ACKNOWLEDGMENTS

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