Jet Grouting Practice: an Overview

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ABSTRACT: Jet grouting is one of the most popular ground improvement techniques due to its applicability in almost all soil types. In this overview, the historical progress of technology development in jet grouting is briefly described, followed by the trace of the development of empirical and theoretical approaches for predicting the achievable diameter of a jet grout column. This paper also introduces a recently developed jet grouting technique called the Twin-Jet method. Twin-Jet method was developed to achieve quick solidification of soft soils by jetting with two types of binders, cement-slurry and sodium silicate (water glass) as an accelerator. This technique is particularly advantageous in horizontal jet grouting applications. Two case histories are presented to demonstrate the performance of Rodin Jet Pile (RJP) method in the soft clayey and sandy soils in Shanghai and the application of the Twin-jet method in sandy soils in South Korea.

KEYWORDS : Soft deposit, Jet Grouting, Diameter, Twin-Jet, Two binders.

1. INTRODUCTION

Jet grouting is a soil treatment technique for stabilizing soft ground by mixing cement slurry with in-situ soil. Jet grouting has been widely used for soft ground modification in various underground projects to form base seals and buried grout struts for deep excavations, structural support around tunnel eyes at the entrance and departure sites of tunnel boring machine, as well as sealing of leaking joints in diaphragm walls (Shen et al., 2008b; 2010; 2012; 2013a; Peng et al., 2011; Sun et al., 2012; Tan and Wei, 2012; Wang et al., 2013). The jet grouting involves the injection of cement slurry under high pressure from a nozzle fixed on a rotating monitor into the ground. The resulting high speed fluid jet erodes the in-situ soil and simultaneously mixes it with cement slurry to form a soil-cement column. Some applications have indicated that the shear strength of the soil-cement column could reach to several mega-pascal (Maswoswe, 2003; Ho, 2009; Shen et al., 2013b).

Jet grouting was initially patented in 1968, under the name Chemical Churning Pile (CCP) method (Nakanishi et al., 1997), which is the fore runner of the single fluid system. With further improvement of the installation process and supporting equipment, alternate systems were developed, including the double fluid system, triple fluid system, multi-fluid method (SSS-MAN), Rodin Jet Pile (RJP) and Metro Jet System (MJS) (Nakanishi et al., 1997; Brill et al., 2003; Burke, 2004).

This paper presents the historical development of jet grouting technology and highlights more recent research activities in Shanghai for infrastructure construction. Recent research activities have focused on the technological development of the Twin Jet method and RJP method in Shanghai.

2. JET GROUTING TECHNOLOGY

2.1 Basic Concept

Figure 1 presents a schematic view of the jet grouting process. A high speed fluid (water jet or grout jet) is injected through small diameter nozzles into the subsoil to erode the surrounding soil, while the nozzles are rotated and lifted towards the ground surface at a constant speed. The eroded soil is simultaneously mixed with the injected grout to form the admixture, and a soil-cement column with a quasi-cylindrical shape would be formed after some days of solidification.

2.2 Conventional Jet Grouting Systems

Based on the different methods of fluid injection, jet-grouting technology can be classified into three basic types (see Figure 2): *i*) single fluid system (only grout), *ii*) double fluid system (grout and air), or *iii*) triple fluid system (water, grout, and air). The single-fluid system utilizes grout as the cutting jet as well as to achieve cementation of the eroded soil. In the double-fluid system, a compressed air shroud is introduced around the grout jet to enhance the cutting distance of the grout jet. In the triple-fluid system, water is used for the cutting jet together with a compressed air shroud, and grout is injected separately through a lower nozzle at much smaller pressure to mix with the eroded soil. The adoption of a lower viscosity fluid such as water (in comparison with that of grout) allows the cutting distance to be further enhanced, especially in cohesive soils.

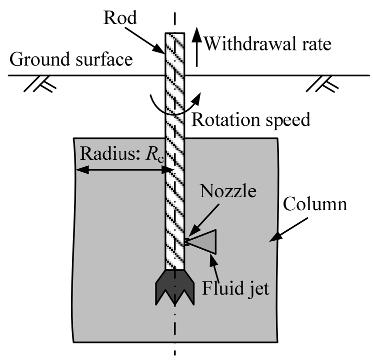


Figure 1 Schematic view of jet grouting technology

2.3 Jet Grouting Operational Parameters

The key jet grouting operational parameters governing the jetting performance are:
(1) Characteristics of jetting fluid (i.e. water-cement ratio of grout);
(2) Pressure and flow rate of jetting fluid;
(3) Jetting time (which is a function of the traverse velocity of nozzle, and hence the withdrawal rate and rotation speed);
(4) Characteristics of nozzle (i.e. nozzle diameter, number of nozzles and nozzle shape).

Table 1 shows the range of jet grouting parameters commonly adopted for three conventional jet grouting systems (Burke, 2004; Lunardi, 1997). The applied fluid pressure for cutting jet ranges in general from 30 MPa to 70 MPa for the single and double fluid systems. In the triple fluid systems, typical injection pressure for the water cutting jet is 30 to 40 MPa, while the grout is introduced of a much lower pressure of 7 to 10 MPa and is just used to mix with the soil eroded by the high pressure water jet. The traverse velocity of the nozzle in the triple fluid system is smaller than that in single and double fluid systems.

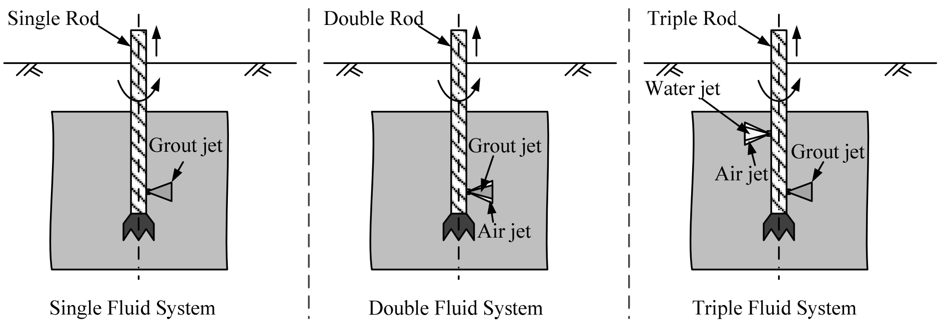


Figure 2 Illustration of conventional jet grouting systems

Table 1 Ranges of jet grouting parameters for conventional jet grouting systems (after Burke, 2004; Lunardi, 1997)

Parameters	**Single fluid system**	**Double fluid system**	**Triple fluid system**
Water pressure, MPa	NA	NA	30~40
Flow rate of water, L/min	NA	NA	80~200
Number of nozzle	NA	NA	1~2
Nozzle diameter, mm	NA	NA	1.5~3.0
Air pressure, MPa	NA	0.7~1.5	0.7~1.5
Flow rate of air, m^3/min	NA	8~30	4~15
Grout pressure, MPa	40~70	30~70	7~10
Flow rate of grout, L/min	100~300	100~600	120~200
Grout density, g/cm^3	1.25~1.6	1.25~1.8	1.5~2.0
Number of nozzle	1~6	1~2	1~3
Nozzle diameter, mm	1.0~4	2~7	5~10
Withdrawal rate, cm/min	15~100	10~30	6~15
Rotation speed, rpm	7~20	2~20	7~15

Note: NA=Non available

2.4 Formation of Jet Grout Columns

Filed experience indicate that, for the same set of same jet grouting parameters, the column diameters formed in different soils are not identical. The cutting efficiency in single fluid system is relatively small, and the typical column diameters formed ranged from 0.9 m to 0.4 m, with decreasing trend from gravelly soil to clayey soil, as shown in Figure 3 (Croce and Flora, 2000). Due to the utilization of compressed air in double fluid systems, the column diameters obtained are 30% to 70% larger than that for a single fluid system (Lunardi, 1997). Figure 4 shows the variation of column diameters with soil type obtained using triple fluid system (Burke, 2004), which suggests that the diameters formed were larger due to increased cutting efficiency, and column larger than 2.0 m is possible.

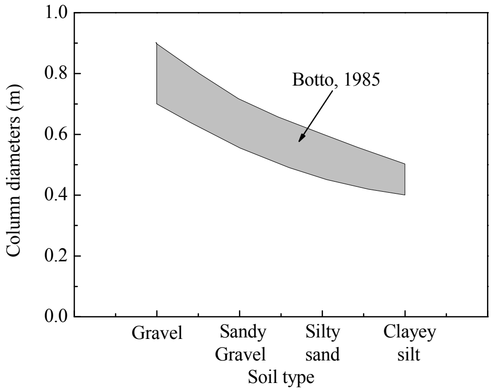


Figure 3 Variation of column diameters with soil type for single fluid system (after Croce and Flora, 2000)

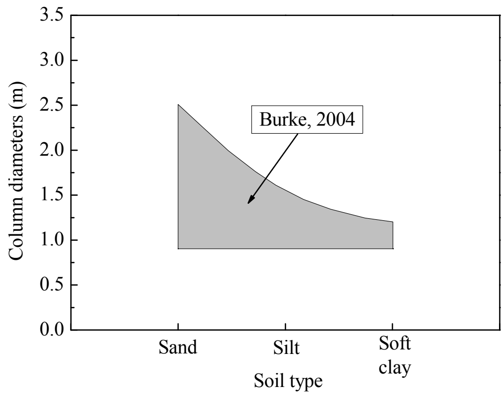


Figure 4 Variation of column diameters with soil type for triple fluid system (after Burke, 2004)

3. HISTORICAL DEVELOPMENT OF JET GROUTING TECHNOLOGY

Jet grouting technology was first invented in Japan in the 1970s (Yahiro and Yoshida, 1973). With the development of technologies in other fileds, there were also many technical improvements to jet grouting in Japan, especially with regards to plant and equipment. Research and development in Japan were mainly performed by two groups, one led by Yahiro and the other by Nakanishi (Xanthakos et al., 1994). Later, jet grouting technology was gradually introduced to many other countries, such as United States, Europe, and China etc.

As shown in Figure 5, introduction of jet grouting as a single fluid system began in the late-1970s in United States during the period of economic downturn in oil drilling services and a corresponding glut of jet grouting equipment became available (Brill et al., 2003). In the mid-1980s, the triple fluid system was introduced, since it can provide a more controllable and safer system in installation. The double fluid system enabled significant savings in cost for many soil conditions and became popular in the 1990s. The introduction of the Super Jet technology from Japan to United States in 2000s enabled further cost saving for mass stabilization with its ability to produce very large diameter columns (Brill et al., 2003). Jet grouting technology was first introduced into Europe in the late-1970s and was mainly applied to water resource and tunneling projects (Coomber, 1986; Lunardi, 1997; Brill et al., 2003; Flora et al., 2007). The research and development of jet grouting in Europe were mainly carried out in Italy, especially in the development of design theory for ground improvement using jet grout columns formed with the single fluid system (Croce and Flora, 2000; Modoni et al., 2006; Modoni and Bzòwka, 2012), using jet grout columns as ground water cut offs in water resource projects (Croce and Modoni, 2007), and jet grouted umbrellas in tunneling project (Flora et al., 2007; Lignola et al., 2008). Development of jet-grouting in China began at the end of 1970s and was first used to construct a retaining structure for an excavation at Baoshan Steel Inc., Shanghai (Xu and Quan, 2004). With the development of large-scale urban construction since 1990s, jet-grouting has been employed in underground construction in mega-cities, such as

Shanghai, Beijing, and Guangzhou. During this period, jet-grouting technology was also applied to large-scale hydraulic projects, such as the Three Gorges Dam project of Yangtze River, and the Xiaolangdi project of Yellow River. Since 1990, China has since become the leading country with the largest volume of jet-grouting in the global construction industry.

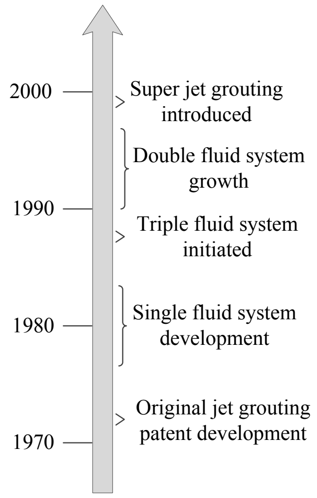


Figure 5 Historical development of jet grouting in United States (after Brill et al., 2003)

Figure 6 shows several typical methods in historical development of jet grouting. As can be seen, the methods developed earlier were Chemical Churning Pile (CCP), Jambo Special Pile (JSP) and Column Jet Pile (CJP), which corresponded to the single, double, and triple fluid systems, respectively. In order to meet the demands for increasing the dimensions and mechanical properties of jet grout columns, further technical improvements have been introduced, such as Super Jet technology, X-Jetting technology, Rodin Jet Pile (RJP) technology, Twin-Jet Method and Metro Jet System (MJS) technology (Essler and Yoshida, 2004; Shen et al., 2008a, 2009a).

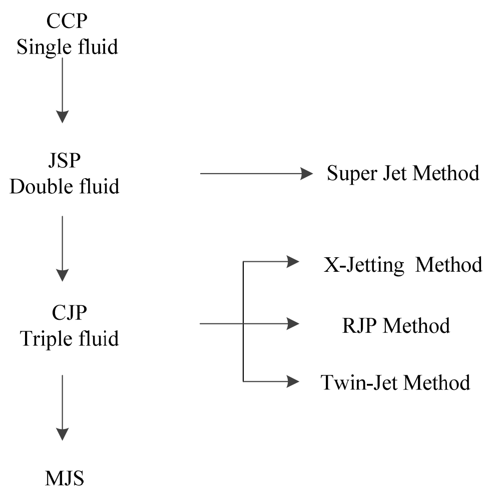


Figure 6 Typical methods in historical development of jet grouting

3.1 Super Jet Technology

Based on the advancement in the tooling and support equipment, Super Jet technology has been developed to produce larger jet grout column (Brill et al., 2003). Figure 7 shows the illustration of Super Jet technology. As can be seen, it is developed based on the conventional double fluid system. For creating a larger jet grout column, this technology utilizes two opposing nozzles to eject high pressure grout (30 MPa) shrouded by compressed air (0.7~1.05 MPa). Compared to the conventional double fluid system, Super Jet technology has a higher injection volume of grout flow in construction, and hence the diameter obtained by Super Jet technology can achieve about 5 m in some case (Essler and Yoshida, 2004).

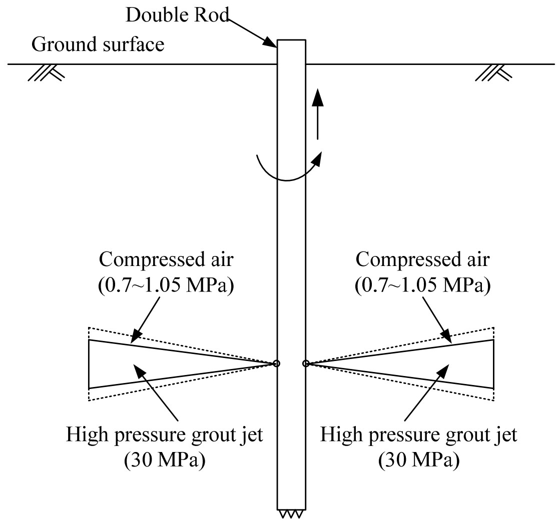


Figure 7 Illustration of Super Jet technology

3.2 X-Jetting Technology

Figure 8 shows the illustration of X-jetting technology, and it can be seen that X-jetting technology is developed on the basis of the conventional triple fluid system (Essler and Yoshida, 2004). In X-jetting technology, a pair of colliding erosion water jets (40 MPa) which is shrouded by compressed air (0.6~1.05 MPa), is adopted to produce a more controlled erosion range of soils, and then the low pressure grout jet is ejected from a lower nozzle to mix the eroded soil for forming a more uniform and controlled diameter of jet grout column (Burke, 2004).

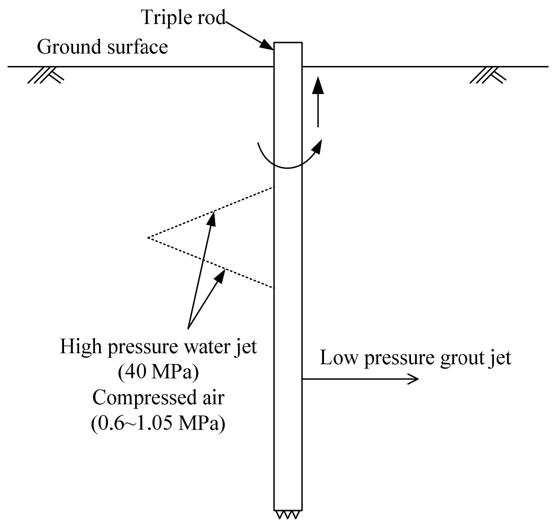


Figure 8 Illustration of X-jetting technology

3.3 Rodin Jet Pile Technology

A variation of the conventional triple-fluid system, called RJP technology, was introduced by Tsujita (1996). In RJP technology, both the water and grout jets are simultaneously injected under high pressures (Shen et al. 2009b), such that the soil is subjected to two stages of erosion, initially by the water jet, then followed by secondary erosion by the grout jet. The exposure of the soil twice to the cutting action of the jets enables a larger column to be formed. Figure 9 shows the illustration of RJP technology.

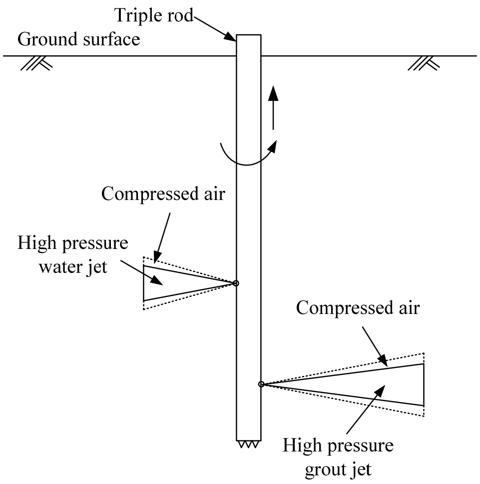


Figure 9 Illustration of RJP technology

3.4 Twin-Jet Method

To achieve a quick gel of soft ground after jet grouting, the hardening process of an admixture of grout-soil must be accelerated by adding a binder into the admixture of grout-soil. When water-glass is selected as the binder, the admixture of grout-soil can gel within 5 to 10 seconds. Thus, the Twin-Jet Method is developed based on this traditional triple fluid system (Kim, 2008; Shen et al. 2009a). Figure 10 shows the schematic diagram of the materials using the transporting process in the formation of a jet grout column while using the Twin-Jet Method. In the Twin-Jet Method, high-pressurized grout shrouded by compressed air is jetted out to erode the soil, and the admixture of grout-soil is formed. Then, the water-glass solution shrouding the high-pressurized grout is jetted into the admixture for a quick gel, and a jet grout column can be formed after hardening.

3.5 Metro Jet System Technology

As jet grouting involves the injection of large volumes of water or grout into the soil, significant impact on the ground can be expected, such as lateral movement of soils and ground upheaval. By transporting out the spoil timely during jet grouting, a new jet grouting technology named MJS technology has been developed for reducing the inverse impact (Nakashima and Nakanishi, 1995).

Figure 11 presents the sectional view of composite pipe used in MJS technology, in which there are many pipes with different purposes, and this is highly different from conventional jet grouting systems that have 1 to 3 channels in general. As shown in Figure 11, the different purposes of various pipes can be listed as: (1) for injecting the high pressure grout (grout pipe), (2) for injecting high pressure water to erode soil (water pipe I), (3) for providing help to transport out the spoil (water pipe II), (4) for injecting compressed air (air pipe), (5) for the set of cables linking the sensor (cable pipe), (6) for transporting the additive (additive pipe), (7) for transporting out the spoil induced during jet grouting.

4. HISTORICAL DEVELOPMENT OF SOIL EROSION MECHANICS IN JET GROUTING

The interaction mechanism between a high speed fluid jet and soil is highly complex and is still not explicitly understood at present. Kanematsu (1980) suggested a number of effects could be included in the interaction of soil and high speed water jet: 1) hydrodynamic pressure; 2) pulsation load of water jet; 3) water wedge effect; 4) impingement force of water mass; 5) cavitation. For different soils, the interaction between the high speed jet and soil is also different. It is generally accepted that, for gravelly soils, permeation of the grout through soil pores would be the important, while for sandy and clayey soils, the mixing and replacement of the soil by the grout would be important (Miki, 1985; Bell, 1993; Croce and Flora, 2000; Modoni et al., 2006; Ho, 2007). In jet grouting, the degree of soil erodibility is not identical for different soil conditions, so the diameters achieved by the same jet grouting parameter may also be different. Field experience indicates that high plasticity clays with significant cohesion are more difficult to erode than granular soils, as shown in Figure 12 (Burke, 2004). The critical erosion velocity of soil (the minimum value of jet velocity that will initiate soil erosion) has been used by various investigations to represent the soil erodibility (Dabbagh et al., 2002; Briaud, 2008). The critical erosion velocity is a function of the soil properties, and has been expressed in terms of the soil shear strength by several researchers (Dabbagh et al., 2002; Modoni et al., 2006; Wang et al., 2012). Nevertheless, the existing methods for calculating critical erosion velocity do not consider the effect of grain size distribution and soil stress level.

5. EXISTING METHODS FOR PREDICTION OF JET GROUT COLUMN DIAMETER

The factors influencing the diameter of the jet-grouted column include soil properties and jet parameters. The existing methods for estimating jet grout column diameter are either based on an empirical approach or a theoretical approach (Table 2). The empirical methods were developed based on observations derived from jet grouting field trials and attempt to correlate column diameter to the various operational parameters mathematically using a power law. Hence, these relationships do not have a clear physical meaning. In the empirical methods, certain operational parameters (such as jetting pressure, flow rate and withdrawal rate of the nozzle) have been considered, however, other important parameters (such as nozzle diameter, effect of air shroud in double and triple fluid systems, rotation speed, grout characteristics and soil properties) have been ignored. The empirical coefficients were derived from specific ground conditions, and it would be difficult to apply them for other jet grouting projects where the ground conditions are different.

The theoretical methods were based on theories of turbulent flow and soil erosion (Modoni et al. 2006; Ho 2007; Shen et al., 2013c). With these methods, the physical process of jet grouting, i.e., the interaction between fluid jet and soils, can be reasonably described. Modoni et al. (2006) presented three models for describing the physical process of jet grouting in different soils: a seepage model for gravelly soils, and an erosion model both for sandy soils and clayey soils.

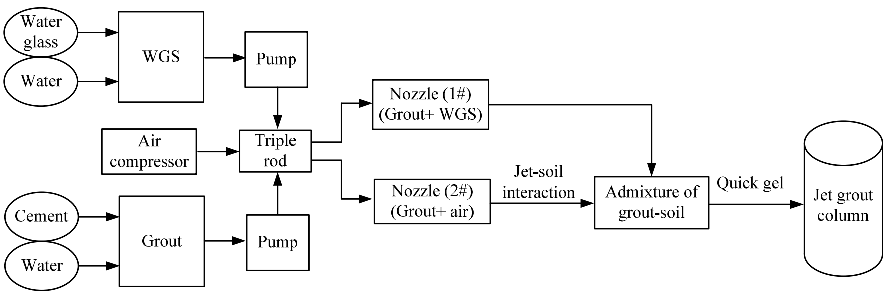


Figure 10 Illustration of Twin-Jet method

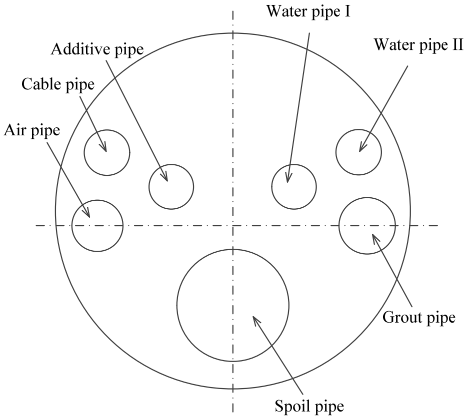


Figure 11 Sectional view of composite pipe used in MJS technology (after Nakashima and Nakanishi, 1995)

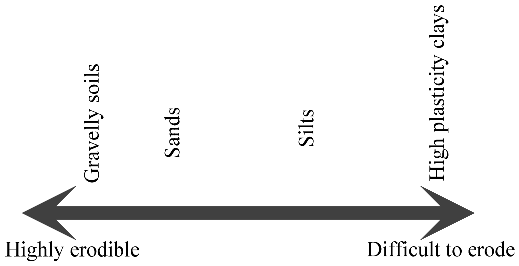


Figure 12 Soil erodibility scale for jet grouting (after Burke, 2004)

For the very pervious soils (gravels and sandy gravels), Modoni et al. (2006) presented a seepage model to simulate the phenomenon of soil pore filling by an injected fluid. In the erosion models for sandy and clayey soils, the rate of penetration of the fluid jet in the soil and the duration of action of the jet on the soil are considered to be important factors governing the achievable column diameter. It was determined that the penetration rate of the fluid jet increases with the increase in fluid velocity and decreases with the increase in soil resistance, while the duration of action of the fluid jet increases with the height of each lift step and decrease in withdrawal rate of the rod. In the derivation of the penetration rate and duration of jetting action, certain variables such as fluid properties, flow rate, withdrawal rate, nozzle diameter and number of nozzles as well as soil resistance have been considered, while other factors such as the effect of compressed air (in the case of double- and triple-fluid systems), rotation speed, and particle size distribution have been neglected.

Table 2 Existing methods for predicting jet grout column diameter

Methods	Equations		References
Empirical approach	$D_0 = k p_g^{k_1} Q_g^{k_2} N^{k_3} V_m^{k_4}$	(1)	Shibazaki (2003)
	$D_0 = n_1 \left(p_g Q_g / v_s \right)^{n_2}$	(2)	Mihalis et al. (2004)
Theoretical approach	$D_0 = 2\int_0^{t^*} V_c t^* dt^*$	(3)	Modoni et al. (2006)
	$D_0 = 12.5 d_0 \sqrt{\dfrac{p_g - p_0}{q_{bu}}} + D_r$	(4)	Ho (2007)

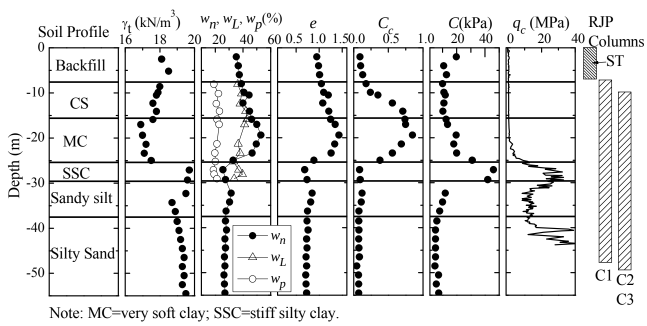
Note: k, k_1, k_2, k_3, k_4, n_1, and n_2 are empirical coefficients.

Ho (2007) presented a simplified method to estimate the column diameter, which accounted for several important parameters (such as jetting pressure, nozzle diameter and soil bearing resistance). However, other parameters such as the effect of compressed air, particle size distribution, rotation speed, withdrawal rate and grout properties) have not been considered.

6. CASE HISTORIES

6.1 Application of RJP Method in Shanghai

In 2004, the RJP method was adopted in the tunnel construction of Metro Line No. 4 (Shen et al., 2009b). The construction site in this project was located along the west bank of the Huangpu River in Shanghai. The tunnel was constructed using open cut excavation. The total length of the excavation was about 250 m with a depth of 43 m. A diaphragm wall system served as the retaining wall for the excavation. The diaphragm wall was 1.2 m thick and 65 m deep. The subsurface profile consisted of backfill, clayey silt, soft normal consolidated marine clay, stiff dessicated silt clay, medium sandy silt, and dense silt sand (Figure 13). The ground water level fluctuated between 1 to 2 m below the ground surface. The backfill layer was 7.5 thick with undrained cohesion of 10-20 kPa. The clayey silt layer (CS) varied from lowly to highly compressible, with natural water content approximately equal to the liquid limit and a rather uniform cohesion of about 10 kPa. The marine clay was medium to highly compressible with high water content that were high significantly higher than the liquid limit. The cohesion strength of the marine clay increased with depth ranging from about 15 to 35 kPa. The stiff silty clay layer was of very low compressibility, with natural water contents less than 25% and high cohesion of 40 to 50 kPa. The sandy silt exhibited a rather uniform strength with the cone resistance averaging about 12 MPa. The bottom silty to fine sand layer extended over a thickness of 17 m with CPT resistance greater than 12 MPa and increasing with depth. Detailed information can be found in Xu et al. (2009) and Shen et al. (2009b).



Note: MC=very soft clay; SSC=stiff silty clay.
γ_t=unit weight; w_n=water content; w_p=plastic limit; w_L=liquid limit; e=void ratio;

Figure 13 Geotechnical profile and soil properties at the RJP test site (after Shen et al. 2009b)

Field trials were conducted to confirm the efficacy of RJP installation in the various soil deposits (Figure 14). Four sets of test columns (labeled as ST, C1, C2, and C3) were installed. Test column ST was installed from the ground surface prior to the excavation. Columns C1, C2 and C3 were installed along the alignment of jet grout wall using standard RJP parameters to confirm the efficacy of RJP in different types of soils. C2 and C3 were used to verify the relationship among diameter, strength, and jetting parameters.

The field trials showed that the eroding ability and uniformity of mixing in the various soil layers were significantly different. Within the backfill, clayey silt, and marine clay (from ground surface to a depth of 25 m), the columns were very well formed and the cement was uniformly mixed with the in-situ soil. The column within the stiff clay layer (from the depth of 25 to 29 m), also demonstrated a good quality; however, the diameter of the columns were limited to about 0.8 to 1.2 m due to the poor erosion in this soil layer. For the sandy silt and silty sand (layers below 30 m depth), the eroded distance was much larger than that in the stiff silty clay. However, the uniformity of mixing in these two layers was observed to be very poor. In general, the diameter of the solidified columns varied between 0.8 m and 3.3 m, and the unconfined compressive strength (UCS) after 28 days was between 0.9 and 8.1 MPa.

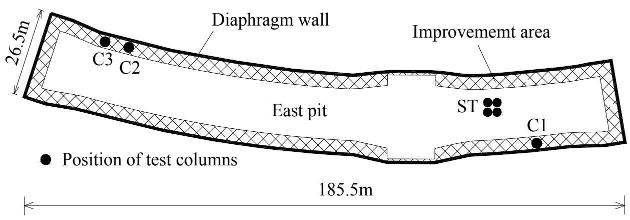


Figure 14 Layout of test columns using the RJP method (after Shen et al. 2009b)

6.2 Application of Twin Jet Method in South Korea

This case history describes the use of the Twin-Jet method to improve a historical bridge foundation in South Korea. The Nam Ji-Kyo Bridge, located at Chang-Ryeong, is listed as South Korea Historic Cultural Property No.145. The bridge was constructed of iron using rivets and was completed in 1952 (Figure 15). The original foundation of the bridge consisted of concrete piles. Although the original design allowed vehicles to pass through the bridge, it is now restricted to only pedistrains.

Figure 15 View of historical bridge Nam Ji-Kyo in Chang- Ryeong, South Korea

Figure 16 shows a sectional view of the soil improvement zone using the Twin-Jet method and monitoring instruments. Two bridge piers P6 and P7 were required to be strengthened. The subsurface profile at the site comprised four soil types: silt, sand, sandy gravel and soft rock. Standard Penetration Test (SPT) blow counts for soils above the soft rock were N=5 (silt), N=12 (sand) and N>30 (sandy gravel).

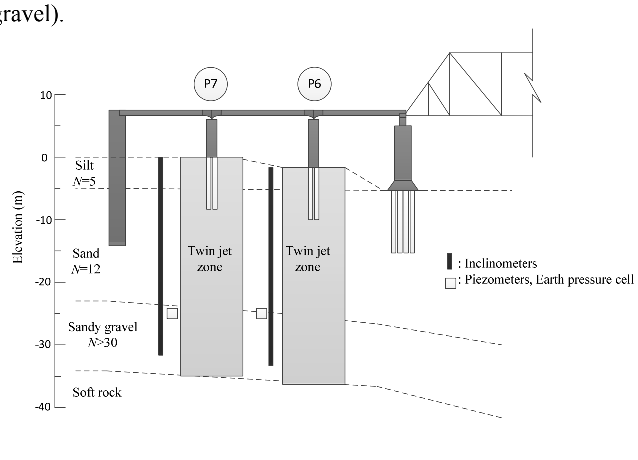


Figure 16 Cross section showing soil improvement zones using Twin-Jet method

Figure 17 shows the plan view of the soil improvement zones under piers P6 and P7 and monitoring instruments installed in the ground. Two piezometers, two earth pressure cells and four inclinometers were installed. The piezometers and earth pressure cells were located close to the interface of the sand and sandy gravel layers. Figure 18 shows the layout of twin jet-grouting columns. The design diameter was 0.8 m at spacing of 0.7 m center to center. During jet grouting, the pore water pressure, earth pressure and lateral movement of the soils were monitored. After construction, cored samples were extracted from the column to examine the in-situ quality of the cement-soil product.

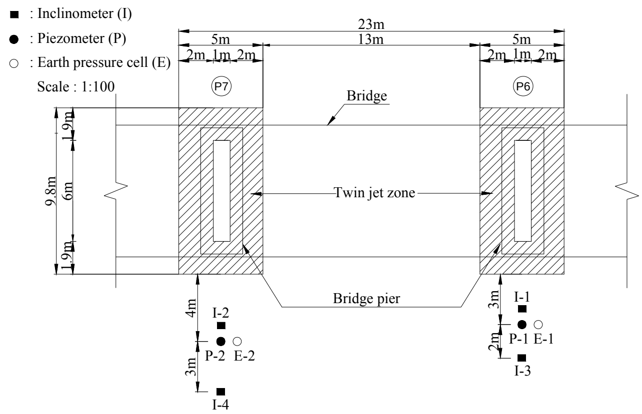


Figure 17 Plan view of layout of soil improvement zones and monitoring instruments

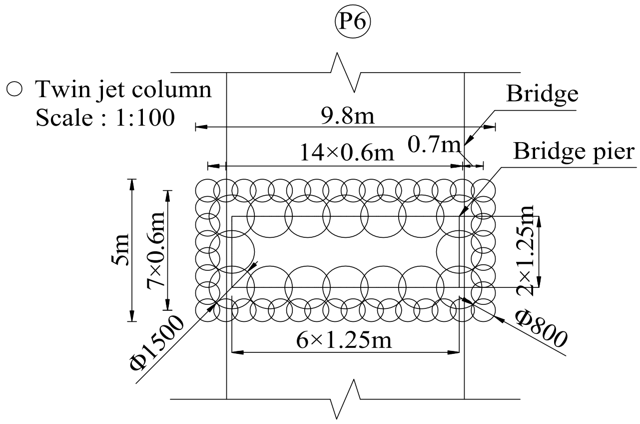


Figure 18 Plan layout of twin jet-grouting columns

Figure 19 shows the measured lateral soil movements induced by installation of jet grouting using the Twin-jet method around the two bridge piers P6 (Figure 19a) and P7 (Figure 19b). It can be seen that the maximum lateral soil movements reached 260 mm after field construction. The measured lateral soil movements along the depth of the columns were approximately uniform as observed at each inclinometer. Figure 20 presents the observed variation of excess pore water pressure developed in the ground during jet grouting. As shown, installation of twin-jet columns can induce excess pore water pressures up to about 9 kPa. It can be seen that, the generated excess pore water pressures were temporary and dissipated over 4 to 5 days after completion of jet grout columns installation.

Figure 21 shows the observed incremental earth pressure induced by the installation of twin-jet columns. Earth pressure cell E1 increased to a maximum of about 6 kPa. However, a decrease in earth pressure was observed at earth pressure cell E-2 near P7, suggesting that the flow of grout through the voids in the soil at this location was fairly rapid and relatively unimpeded. Figure 22 shows the continuous cored samples obtained from the twin-jet columns and suggests that the quality was excellent.

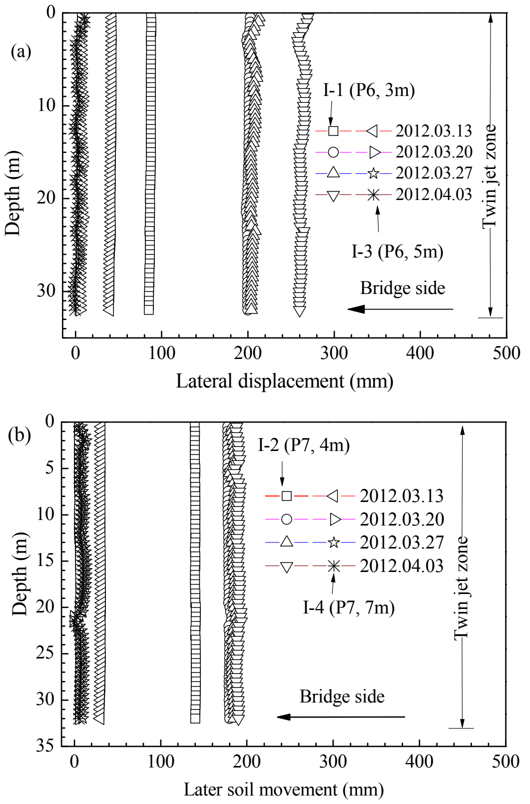


Figure 19 Effects of twin jet-grouting on lateral soil movements of adjacent soils for (a) Inclinometers I-1 (P6, 3m), and I-3 (P6, 5m); (b) Inclinometers I-2 (P7, 4m), I-4 (P7, 7m)

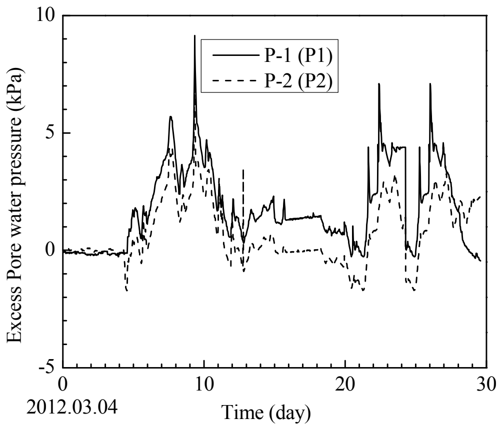


Figure 20 Observed variation of excess pore water pressure

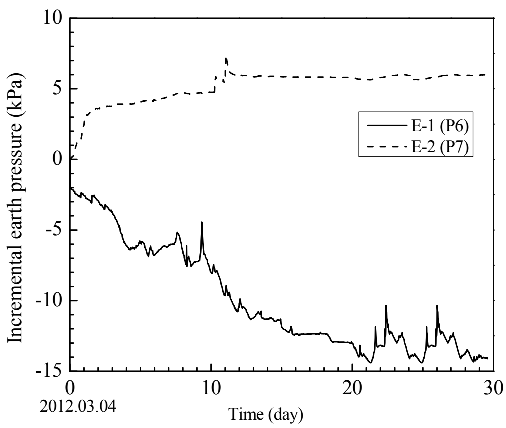


Figure 21 Effects of twin jet-grouting on changes in lateral incremental earth pressure of adjacent soils

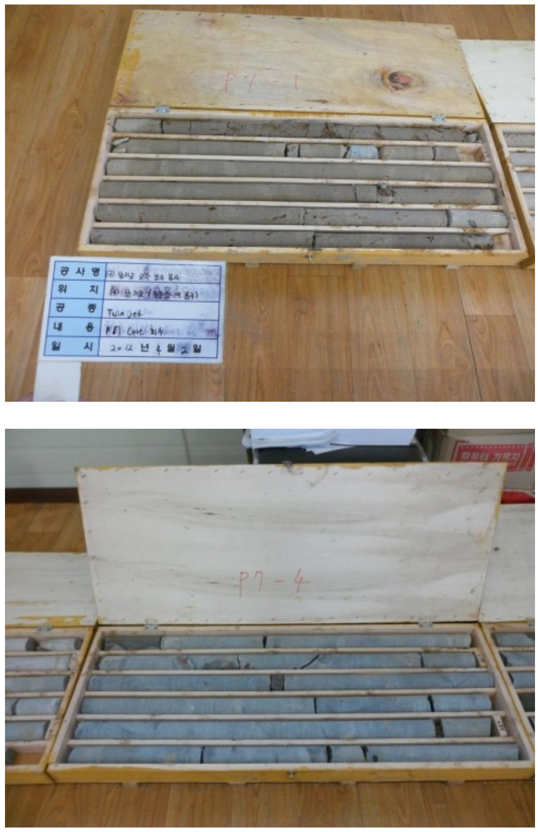


Figure 22 Coring samples from the twin jet columns

7. CONCLUSIONS

This paper provides an overview of the historic development of jet-grouting technology and highlights the advancement achieved in recent years. With the progress of urbanization worldwide, the applications of jet-grouting method have been confronted with more challenging situations than those before. Greater attention was focused on the installation process, resulting in the development of the RJP technology in Shanghai and Twin-jet method in South Korea. The following conclusions can be made:

(1) Experience with the application of the RJP method in the soft soil deposits of Shanghai indicated that large diameter columns with high quality mixing can be achieved in clayey soil. In sandy soil, although column diameters up to 2.0 m were obtained, the uniformity of the resulting soil-cement mix with the column was highly variable with unconfined compressive strengths ranging from 0.9 to 8.1 MPa.

(2) The Twin-Jet method was developed to achieve instant solidification of soft grounds using sodium silicate solution (water glass). Because the admixture of grout-soil can be gelled within 5 to 10 seconds, the soft ground can be quickly solidified, hence significantly increasing the site productivity. This new technology is implemented at low operating cost to enhance work efficiency up to about three times.

(3) Experience in South Korea suggests that twin-jet method can be successfully applied in sandy soils. The field observations show that the uniformity of jet grouted column was excellent. However, the lateral soil movement induced by the installation of twin-jet method may be large, up to about 260 mm.

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