STATE OF PRACTICE OF JET GROUTING IN SHANGHAI: FROM TECHNOLOGY DEVELOPMENT TO SCIENTIFIC RESEARCH

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ABSTRACT: Shanghai has enjoyed a rapid economic development in the past 30 years. Many mega-scale infrastructures, including subways, high-speed railways, highways, hydraulic facilities, and so on, have been/are being constructed. Recently in Shanghai, jet-grouting method is a useful and effective technology for soft ground improvement in various underground projects. This paper presents the recent development of jet-grouting methods in Shanghai for the infrastructure construction. Recent research activities and findings including theoretical and technological development are presented. A case history of practice of Rodin Jet Pile (RJP) method is firstly introduced. Then, more attention is paid on the newly developed technology named Horizontal Twin-Jet Grouting Method (HTJGM), including the construction equipment, construction procedure, and a case history using this new method. At last, an approach to predict the diameter of jet-grouted column based on turbulent flow theory and soil eroding theory is presented.

Keywords: Ground improvement; Jet grouting; Case history; Column diameters.

INTRODUCTION

Shanghai is located on the south bank of the estuary of the Yangtze River. The most part of the land region of Shanghai is a soft deltaic deposit formed during quaternary era (Xu et al. 2009; Shen and Xu 2011). The quaternary deposit in Shanghai has high water content, high compressibility, high sensitivity and low strength (Xu et al. 2009). With rapid economic development of Shanghai, many underground facilities, such as metro tunnels and deep excavations, are constructed in the soft deposit of Shanghai (Sun et al. 2012). In order to keep the safety during construction, this soft deposit need to be improved with soil-cement mixing and/or grouting technologies (Shen et al. 2008), in which jet-grouting method is a useful and effective technology (Shen et al. 2009a; 2009b).

Jet grouting technology is based on the injection of the high speed fluid into the subsoil through small-diameter nozzles to erode the soil. The eroded soil is mixed with injected grout to form a soil-cement column in a quasi-cylindrical shape. According to the number of injected fluids, there are three main jet-grouting methods including single fluid (only grout), double fluid (grout and air), and triple fluid (water or accelerator, grout, and air) (Burke 2004; Fang et al. 2006).

The objective of this paper is to present the recent development of jet-grouting methods in Shanghai for the infrastructure construction. Recent research activities, including theoretical and technological development, are presented.

RJP METHOD: PRACTICE IN SHANGHAI

In RJP, the in-situ soil is eroded twice: the first erosion is conducted under high pressure water surrounded by compressed air and the second erosion is conducted under high pressurized cement slurry, which is also surrounded by compression air. The surrounded compressed air can improve the eroding ability of the high pressure fluid flow. Then, the eroded soil is mixed with the high speed cement slurry to form a soil-cement column. The diameter of the column can be enlarged via the double erosion of in-situ soil.

In order to confirm the efficacy of RJP in the soft deposit of Shanghai, a series field construction tests were conducted at the tunnel remediation project of Metro Line No.4. The test construction site in the remediation

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project of Metro tunnel in line No.4 is located along the west bank of the Huangpu River in Shanghai. The tunnel was reconstructed using open-cut method and the excavated foundation pit was separated into three parts: east, middle, and west part. Four sets of test columns (labeled as ST, C1, C2 and C3) using the RJP method were installed in east pit. Fig. 1 illustrates the layout of the columns. ST was constructed inside the pit before pit construction from ground surface to a depth of 7.0 m to check the efficacy of different jet grout method such as RJP, TRG, and SJS. In this paper only RJP column is presented. Column C1 was installed from the depth of 7.0 m to a depth of 46 m and it was installed using standard RJP parameters to confirm the efficacy of RJP in different type of soils. The other two columns, C2 and C3, were constructed from 10 m to 50 m below the ground surface and these two columns are used to verify the relationship among diameter and strength of jet grouted column and construction parameters.

Site Conditions

The total length of the pits was about 250 m and the excavation depth reached 43 m. A diaphragm wall system served as the retaining wall for the excavation. The thickness of the diaphragm walls were 1.2 m and the depth of the walls were 65 m.

![Diaphragm wall](image)

**Fig. 1 Layout of the four sets of test columns using the RJP method (Shen et al. 2009b)**

Strength and Diameters of Jet Grouted Columns

Field investigations on the diameter and strength of the columns were performed during the excavation of the pit. The diameter and unconfined compressive strength (UCS) of the three columns were measured and the uniformity of mixing was investigated layer by layer. The edge of column (to determine diameter) and uniformity of the grout column were determined by three approaches: manual cone, visual observation and manual excavation. In the clayey soil layer, manual cone was mainly used. The position, where the cone resistance obviously decreased, was considered as the edge of the grout column. In the sandy soil layer, the edge of the grout column can be directly observed between the grout column and the surrounding soil. Moreover, the difficulty or easiness when manual excavation by spade is an another mean to determine the column edge. Then, the diameter was directly measured using steel tape in various directions and the average value was set as the column diameter. The uniformity of the RJP columns was evaluated by visual observation. If a RJP column had smooth surface with no cement blocks or soil clods, the column could be considered as uniformity. Finally, the samples of the RJP columns were taken and the unconfined compression test was conducted after 28 days curing to determine UCS strength in the laboratory.

Table 1 tabulates the observed result on the quality of the columns, which indicates that in different soil layer the eroding ability and mixing uniformity are much different owing to the different of soil properties. In the layers of backfill, CS, and MC (from the ground surface to the depth of 25 m), column was in a very good state and the cement uniformly mixed with soil. In SSC layer...
(from depth of 25 to 29 m), column can be created in a good quality; however, the eroding ability in this layer is very poor. The diameter of the column is only about 0.8 to 1.2 m. In the layers of sandy silt and silty sand (under 30 m), the eroded range is much larger than that in the upper SSC. However, the mixing uniformity in these two layers is very poor.

Table 1 Diameter and uniformity of the RJP columns in different soil layers (Shen et al. 2009b)

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth, m</th>
<th>Diameter, m</th>
<th>Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backfill</td>
<td>&lt;7.5</td>
<td>2.0~3.0</td>
<td>uniform</td>
</tr>
<tr>
<td>CS</td>
<td>7.5~16</td>
<td>1.6~2.6</td>
<td>uniform</td>
</tr>
<tr>
<td>MC</td>
<td>16~25</td>
<td>1.8~3.3</td>
<td>uniform</td>
</tr>
<tr>
<td>SSC</td>
<td>25~30</td>
<td>0.8~1.2</td>
<td>uniform</td>
</tr>
<tr>
<td>Sandy silt</td>
<td>30~38</td>
<td>1.9~2.3</td>
<td>non-uniform</td>
</tr>
<tr>
<td>Silty sand</td>
<td>&gt;38</td>
<td>~2.0</td>
<td>non-uniform</td>
</tr>
</tbody>
</table>

Fig. 3 illustrates the distribution of the diameter of ST and C1 to C3 columns with depth. The column diameter at the depth over 25 m was larger than 1.8 m. The maximum diameters were over 3.0 m, which were found in the backfill layer and the very soft clay layer. At these depths, the soil layers were comprised mostly of soft soil with a CPT resistance less than 0.5 MPa. Therefore, the resistance ability of these layers to the erosion from high pressure fluid jetting is weak. The eroded range induced by jetting fluid under high pressure in these layers could reach a larger value. For the depth between 25 m and 30 m, the diameter decreased to 0.8 m to 1.2 m. The soil layer at this depth is the stiff silt clay with much high cohesion. In this layer, the soil strength increased to a CPT resistance over 25 MPa. The decrease of diameter of RJP column is due to the increase of cohesion of the soil layer, which made the erosion of in-situ soil be more difficult than that in sand and clay with low cohesion (Burke 2004). In the sandy silt layer, the column diameter increased to 2.0 m though the CPT resistance was over 12 MPa. When the RJP method is applied in a sand layer, localized liquidizing and cavitations may be occur due to the water jet under high pressure. This makes the erosion in a sandy layer much easier; therefore, a larger column diameter can be formed in sandy layers. However, sand and cement in the liquid state of the admixture may separate each other before hardening (and/or gelling). Consequently, the uniformity of soil-cement admixture in sand layer becomes very poor.

Fig. 3 also illustrates the UCS of the RJP columns with depth. The UCS of the RJP columns also varies with soil type. The UCS of the RJP columns over a depth of 20 m, where the soil types are mainly clayey soil, ranged from 0.9 to 2.5 MPa. The UCS in the stiff clay was slightly larger than that in the upper soft clay. The reason may be due to the high strength of the stiff clay and the uniform mixing of soil and cement. The UCS of the RJP column from a depth of 30 m to 46 m, where the soil is sandy silt, is very scattered and varied from 0.8 to 8.1 MPa. In this study, there is no obvious relationship between construction parameters and UCS.

The great difference of the UCS at this depth was due to the non-uniform mixing of soil and cement. Although the diameter of eroding during RJP column construction reached 2 m, the field observations showed that the mixing uniformity in the sandy layer is very poor and there is some cement blocks separated from the sandy soil. Therefore, the samples taken from the column are either loose sandy soil or gelled cement block, instead of the well mixed soil-cement column. The UCS of the cement block was over 8 MPa and was much higher than that of the soil-cement column. In order to solve this problem, a new technology called Twin-Jet was invented, in which cement slurry and an accelerating agent such as sodium silicate (and/or other environmental friendly material) is jetted into ground simultaneously and mixes with sandy soil and the admixture can be gelled within several seconds, that is, the liquidizing admixture can become plastic stick material immediately after jetting (Kim 2004; Shen et al. 2009a).

TECHNOLOGICAL DEVELOPMENT: HTJGM

Horizontal Twin-Jet Grouting Method (HTJGM) is developed for instant solidification of soft ground using two types of binders. This technology is based on the common understanding that the admixture of cement and its accelerator can be gelled in several to tens of seconds. Two types of binders (cement and its accelerator) are jetted under high pressure and mixed at the moment.
when they are ejected from nozzle. Then, the admixture is mixed with the in-situ soil to achieve the instant gelling of the soft ground. More details can be referred in Shen et al. (2009a).

Fundamental Concepts of HTJGM

It has been known that accelerating additives, such as sodium silicate, can speed up the gel of cement. The admixture of cement and accelerator can be gelled in several to tens of seconds while the gelling time of unmixed cement is up to several hours. The gelling time of the admixture will vary with the mixing ratio of accelerator to cement. Therefore, choosing the appropriate mixing ratio is the key to the improvement effect of jet grouting when two types of binders are utilized.

Fig. 4 Variation of mixing ratio as the gel time (Shen et al. 2009a)

Fig. 4 illustrates the relationship between the mixing ratios of sodium silicate to cement and the initial gelling time of cement-silicate admixture. The water-cement ratio of cement slurry is generally 1:1 (mass ratio). The concentration of sodium silicate is from 10 to 30.4 baume degree. As shown in Fig. 4, the initial gelling time decreased rapidly with the increasing content of sodium silicate while total amount of sodium silicate was less. The initial gelling time was shortest (about 3~5 seconds) when the mixing ratio of sodium silicate to cement is 0.25:1. Then the initial gelling time went up to about 30 seconds as the mixing ratio reached 1:1.

Equipment for HTJGM

Fig. 5 schematically illustrates the composition of equipment for horizontal twin-jet grouting, including the drilling and jetting system, the grouting system, and the liquid transporting system. The drilling and jetting system consist of a horizontal drill rig, a triple rod, a three-channel swivel, and an injection monitor with multiple nozzles (as shown in Fig. 5(b)). The grouting system includes a high pressure pump for injecting highly pressurized grout, a low pressure pump for feeding accelerator fluid, an air compressor for generating pressurized air, and other facilities employed for these pumps. The grouting facilities are connected to the triple rod through the three-channel swivel.

Fig. 5 Composition of the equipment for horizontal twin-jet grouting (Shen et al. 2009a)

Fig. 6 shows the triple rod, which is used for drilling and transporting the pressurized liquid and air flow to the monitor. The rod is composed of three coaxial steel pipes, including the inner pipe (first pipe), the second pipe and the outer pipe (third pipe). The inner pipe is connected to the high pressure pump for transporting high pressure grout or water. The second pipe is connected to the low pressure pump for pumping accelerator fluid. The air compressor is connected to the outer pipe, through which the pressurized air can be transported to the monitor.

Fig. 6 Illustration of triple drilling-jetting rod (Shen et al. 2009a)

Fig. 6 also illustrates the configuration of the monitor, which is mounted at the top end of the triple rod. The monitor is equipped with an oneway valve at the top and two injection nozzles on opposite side. The oneway valve is connected to the inner pipe and can automatically control the liquid flow through the pressure. The foreside nozzle has dual outlets which are connected to the inner pipe and the second pipe, respectively, for injecting high pressure grout and accelerator fluid simultaneously. The rearside nozzle also has dual outlets connected to the inner pipe and the outer pipe, respectively, to jet the pressurized liquid and air at the same time. The first erosion of in-situ soil is performed by high pressure grout shrouded by...
pressurized air erupted from the composite nozzle. Then high pressure grout and low pressure accelerator fluid are coaxially jetted out from the foreside nozzle to erode the ground for the second time and mix with the eroded soil simultaneously.

![Diagram of nozzle types](image)

Fig. 7 Illustration of triple drilling-jetting rod (Shen et al. 2009a)

Fig. 7 illustrates the detailed configuration of the foreside nozzle and the rearside nozzle. The foreside nozzle reduces gradually to several millimeters while the inner outlet recedes into the outer outlet. Within the recession distance of the inner outlet, the outer outlet is converted into funnel-shaped, which can prevent the flowback of high pressure grout from the outlet for accelerator fluid. The rearside nozzle also becomes narrow gradually to several millimeters near the nozzle exit. The slurry was jetted out from the inner outlet and is surrounded by the pressurized air erupted from the outer outlet, which can improve the eroding ability of grout and therefore enlarge the diameter of the solidified column.

Construction Procedure

Prior to installation of the soil-cement columns, jet-grouting parameters should be predetermined. Among them, the amount of cement and accelerator applied per unit soil are the key factors for instant solidification of the ground. To decide the optimal proportion of soil-cement-silicate, laboratory tests will be performed with the soil samples extracted from the site, according to the requirements of initial gelling time and strength of the admixture. Then detailed operation parameters should also be determined, on the basis of the target column diameter, soil properties, stress state and strength of in-situ soil, content of binders. Fig. 8 demonstrates the working process of twin-jet grouting in application to horizontal ground improvement, including the following steps:

**Step 1: assembling of equipment**

The twin-jet grouting equipments are first installed and emplaced at the predesigned position, including the drilling and jetting facilities, the grouting facilities and the liquid transporting pipe system. The pressure range and displacement of the pressurization equipments should meet the design requirements. The pipe system must be well sealed, while the hoses and nozzles for jetting binders and air are kept smooth. A test running should be carried out to check the condition of twin-jet grouting machines before they are put into construction.

**Step 2: alignment of drill rig**

The horizontal drill rig must be placed evenly and firmly. The drill rod should be adjusted to the predetermined orientation. The position of drill holes must be set out strictly according to the design scheme with the errors limited within the allowable range.

**Step 3: drilling**

The drill rod will be rotated into ground at the predesigned position of the target column, and then moved forward at the designed velocity until the target length is reached. In this process, the drill rod is slowly rotated forward while at the same time water is injected through the middle channel to form high speed fluid flow. The high speed water is jetted out from the nozzle at the tip of the monitor and erodes the in-situ soil for the first time. The grouting pressure is generally 2 to 5MPa, which is determined according to the soil properties. When the torque induced on the drill rod is large, the grouting pressure needs to increase to loosen the in-situ soil.

**Step 4: twin-jet grouting**

Drilling and grouting is stopped when the drill rod reaches the designed length. The oneway valve at the top nozzle of the monitor is automatically closed by pressure controlled sensor. Then the drill rod is rotated and retracted backward from the drill hole slowly while opening the control valves to transport the binders in the following order: the air valve, the valve for accelerator, the grout valve. The grout shrouded by pressurized air is first jetted out from the nozzle at the rear of the monitor to erode the ground. Then the admixture of cement and accelerator is injected into soil from the foreside nozzle of the monitor. The high pressure grout shrouded by the accelerator fluid will erode the in-situ soil for the second time. The construction of rotary twin-jet grouting is based on design parameters including grouting pressure, retracting rate, rotation rate.

**Step 5: end of construction for one column**

As the drill rod is retracted to the predesigned position, the valves are closed according to the following order: the valve for accelerator, the grout valve, the air
valve. Then pumps and other facilities need to be shut down to finish the construction of the column. After the construction of one column, the drill rod is moved to the entry position of next column and then work steps, from the second step to the fifth step, are repeated to perform the construction of the next column. This process keeps repeating until the target improvement area is entirely treated.

(1) alignment of drill rig

(2) installation of three-channel switch

(3) horizontal drilling

(4) jet grouting with two binders

(5) end of construction with triple rod retracted out

1-drill rig 2-triple rod 3-siwbel 4-injection head 15-oneway valve

Fig. 8 A typical working process of horizontal twin-jet grouting (Shen et al. 2009a)

Case History of HTJGM

The shield arrival shaft in Baili Station of Shanghai Metro Line 11 is located to the northwest of Shanghai. Horizontal jet-grouting at the entrance site of shield machine was conducted in this project to avoid ground subsidence. Field investigation showed that the soil condition in the construction site was very weak, consisting mostly of fill soil and very soft clay. The fill soil in upper layer was of loose structure with high water content and was in a fluid plastic to soft plastic state. The very soft clay was distributed from 7.0 m to 15.0 m below surface, in which the water content was within 45~50% and the unconfined compression strength was 40 kPa. Horizontal jet-grouting was carried out in this layer at depth from 10 m to 14 m below the ground surface. The designed length of jet-grouting columns was 15 m and the target diameter was 800 mm. The target strength of the solidified column was 1.0 MPa. Two binders used in this project were ordinary Portland cement and sodium silicate, which are harmless to the natural environment. The concentration of the sodium silicate was 30 to 40 baume degree.

Field and laboratory tests were carried out to verify the quality of jet-grouted columns. Core samples of the jet-grouted columns were extracted and the unconfined compressive strength was determined by coring and cone penetration tests. The results indicated that the initial gelling time of the admixture was 10 to 20 seconds and the jet-grouting columns were well constructed and uniformly mixed. The results of coring and compressive strength tests showed the strength of the jet-grouting columns after 14 days curing reached 1.2 MPa. The column diameter was confirmed as at least 1.2 meter. The quality and diameter of jet-grouting columns completely met the design requirements.

SCIENTIFIC RESAERCH: ESTIMATION OF COLUMN DIAMETER

The factors influencing the diameter of the jet-grouted column include soil properties and jet parameters. Some empirical methods have been proposed to analyze the influence of jet parameters. However, these methods do not seem to have clear physical meanings (Shibazaki 2003) and are difficult to apply.

Considering the process of jet grouting, fluid with high speed is jetted to erode the soil, and there exists a penetration distance produced in the soil, and the diameter can be estimated from this penetration distance. There are mainly two theories to get the penetration distance, including i) turbulent kinematic flow theory,
related to the jetting fluid; ii) soil erosion theory. With these thoughts, a simple calculation approach is presented to predict the diameter of a jet-grouted column based on the theory of turbulent kinematic flow (Wang et al., 2012).

According to the theory of turbulent kinematic flow, fluid with a velocity of \( v_0 \) is jetted from a round nozzle. As shown in Fig. 9, the flow region can be divided into two parts: (1) the initial zone, in which the maximum velocity of the fluid along the x-direction \( (v_{\text{max}}) \) equals to \( v_0 \); (2) the main zone, in which \( v_{\text{max}} \) varies with the distance from the nozzle.

When the fluid is jetted on the surface of soil, there can be a critical velocity \( (v_c) \) for soil erosion. Considering the diameter of a rod \( (D_0) \), the radius of the jet-grouted column \( (R_J) \) can be obtained by the following equation (Wang et al., 2012):

\[
R_J = \frac{D_0}{2} + \frac{x_L}{2} + b \frac{4Q}{M \pi d_0 \sqrt{q_u / \rho_{\text{atm}}}} \tag{3}
\]

where \( Q \) = the flow rate of the fluid; \( M \) = the nozzle number on the rig; \( d_0 \) = the nozzle diameter; \( x \) = the distance from the nozzle; \( x_L \) = penetration distance; \( q_u \) = the unconfined compressive strength of the soil-cement; \( \rho_{\text{atm}} \) = the atmospheric pressure; \( b \) = the parameter related to the characteristics of the soil, \( b = a \eta/\alpha \); \( \alpha \) = a constant parameter, which is related to the characteristics of the fluid and the medium (soil for jet-grouting) in the flow region; \( \eta \) = a characteristic velocity with a value equal to the critical velocity when the soil resistance is equal to the atmospheric pressure, and related to the characteristic of the soil.

The value of \( b \) is different for different soil type and the proposed method is applicable for most soil types. The eroding ability of soil with the hydraulic energy of jet-grouting is different for different soil types. Thus, the parameter \( b \) can represent the eroding ability of jet fluid on different soils. Wang et al. (2012) determined the parameter \( b \) based on back analysis of test data, as shown in Fig. 10-12: for very soft clay, \( b = 1.2-2.0 \); for clayey silt, \( b = 0.75-1.4 \); for sand, \( b = 0.25-0.75 \). The parameter \( b \) may be related with the clay content in soils, as indicated in Fig. 13.
CONCLUSIONS

This paper summarized the recently research activities and the technological development of jet-grouting in Shanghai. With the process of urbanization, the applications of jet-grouting method have been confronted with more complicated situations than those before. The following conclusions can be drawn:

1. The application of the RJP method in a soft soil deposit in Shanghai indicates that the diameter of the solidified column was between 0.8 m and 3.3 m, while the unconfined compressive strength of the column after 28 days was between 0.9 and 8.1 MPa.

2. A new jet-grouting technique for instant solidification of soft ground, also called as the Twin-Jet Technology, was proposed. Two types of binders (cement and its accelerator) are jetted under high pressure and mixed when they are jetted out from nozzles. Then, the admixture is churned up with the in-situ soil to achieve the instant solidification of ground.

3. A simple calculation approach to predict the diameter of jet-grouted columns was presented. This approach was based on the theory of turbulent kinematic flow and a parameter was proposed to evaluate the eroding ability of jet fluid on different soil types.

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REFERENCES


