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Supporting measures for improving the spoil slurry flow during jet grouting in soft clay

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Abstract

This study presents a trial test of a jet grouting project in clayey soil. The target of the grouted piles' diameter was $\phi=2.0$ m and $\phi=3.2$ m for each group, the main purpose of the test was to confirm the parameters required for the design. Due to its being able to block sludge easily and its risk to cause the surface to overflow as well as ground displacement during the jet grouting process in the clayey soil, the sludge discharge path was then extended along with waterjet cutting (pre-cutting), and the setting of the sludge discharge hole were utilized. Measurement of the specific gravity of sludge discharge during the jet grouting construction stage was done along with comparing the influence of different measures on the smoothing of sludge discharge. Also, a Shape Accel Array scan (SAA) is used to measure the verticality of the grout hole, and the drilling accuracy should be $\leq 1/200$. The effective pile diameter is detected by the Jet Wave Monitoring (JWM) method. After that, the permeability test is used to verify that the permeability coefficient should meet the design permeability coefficient $k < 1 \times 10^{-5}$ cm/sec. Meanwhile, the strength of the core sampling at the position of the pile diameter $2/3$ diameter should meet the design compressive strength requirements (28-day strength of sandy soil $q_u \geq 20$ kg/cm²; the 28-day strength of the clayey soil $q_u \geq 10$ kg/cm²). Finally, the core sampling at the intersection of the three piles is used to verify that the pile diameter and strength meet the design requirements.

Keywords: jet grouting, clayey soil, ground heave, lateral displacement.

1. Introduction

A pilot test of large diameter with 2.0 m and 3.2 m each with 3 piles was performed with a jet grouting in the clayey soil layer. Jet grouting uses the double tube method (commercial named Rapidjet), the main purpose of the test was to confirm the operating parameters required for construction. Due to it is easy to block the sludge and cause the risk of surface overflow or ground displacement during the jet grouting process in the clayey layer, so extend the sludge discharge path, waterjet cutting (pre-cutting), and the setting of the sludge discharge hole were used. Measured the specific gravity of sludge discharge during the grouting stage and compared the influence of different measures on the smoothness of sludge discharge. During the test, Shape Accel Array scan (SAA) is used to measure the verticality of the grout hole. The effective pile diameter is detected by the Jet Wave Monitoring (JWM) method. After the test is completed, the permeability test is used to verify that the permeability coefficient should meet the design value and that the strength of the core sampling at the position of the pile diameter $2/3r$ should meet the design requirements. Finally, the core sampling at the intersection of the three piles is used to verify that the pile diameter and strength meet the design requirements.

2. Site Condition

The test site is located between Tongxing Road, Xizhi District, New Taipei City, which crosses National Highway 1 to Kangning Street. According to the site investigation, the physical properties of soils are shown in Figure 1. It shows that the groundwater level of the site is approximately 1.7 m below the ground surface. The grouting range (GL 6.97~GL 15.21m) is mainly a soft clay with fine sand, the water content (ω_n) is 10%~30%, the unit weight (γ_t) is 1.83~1.93 t/m³, and the SPT-N value approximately between 3~5.

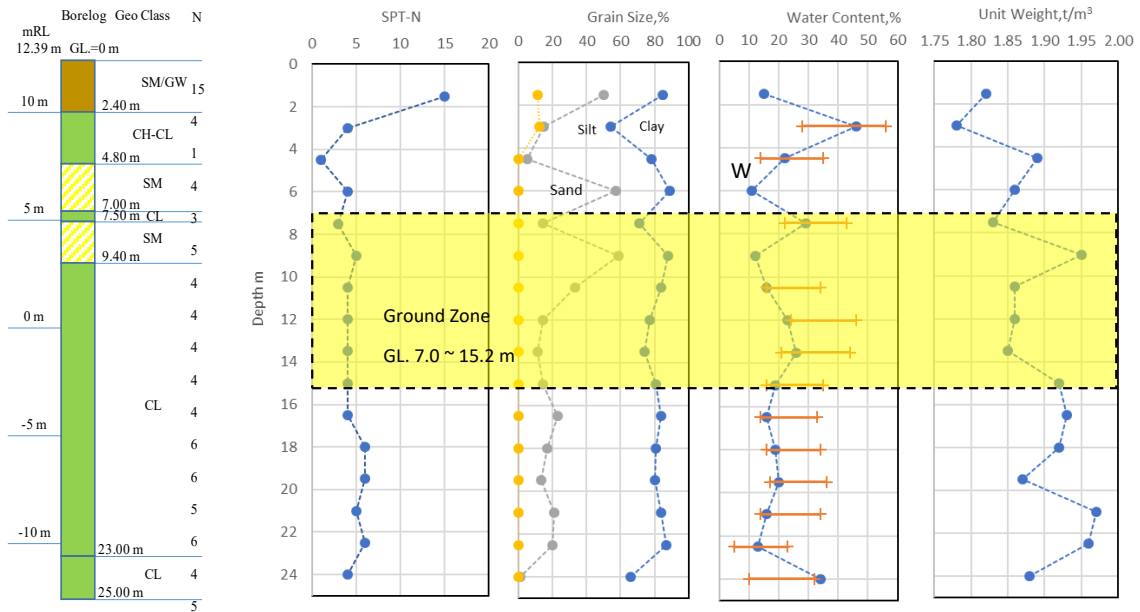


Figure 1: Soil properties of the test site.

3. Design of Pilot Test

The purpose of this study is to verify whether the operating parameters can meet the requirements of the design pile diameter, the design permeability coefficient of the grouted zone, the design strength of the grouted zone, and the design spacing of each grouting pile. The pile diameters (ϕ) of the first group and the second group of test piles are 2.0 m and 3.2 m respectively, and the grouting piles are distributed in a triangular configuration with 3 in each group. In addition to the mentioned requirements for grouting. To ensure the smoothing discharge of sludge during grouting and avoid surface overflow of sludge or large ground displacement occurring during the jet grouting process in the clayey layer, sludge pits were set up to facilitate sludge discharge, and enlarging of the sludge path (increase the diameter of the pipe), waterjet cutting (pre-cutting) and sludge discharge hole, evaluate their effectiveness and differences in the control of sludge discharge. The layout of grouting piles and description of related measures are shown in Table 1 (Wong et al. 1994; Wong and Hwang, 2015).

Design Diameter	grout Pile	extend the sludge discharge path	waterjet cutting	setting of the sludge discharge hole
$\phi=2.0\text{m}$ 	No 2-1 (Type A)	●		
	No 2-2 (Type B)	●	●	
	No 2-3 (Type C)	●	●	●
$\phi=3.2\text{m}$ 	No 3-1 (Type A)	●		
	No 3-2 (Type B)	●	●	
	No 3-3 (Type C)	●	●	●

Table 1: Different measures of sludge discharge.

3.1 Rapidjet Method

Rapidjet Method uses a double-tube (outer diameter=90 mm; inner diameter=31mm) grouting system with two nozzles on the opposite side of the monitor at different levels and uses air and jet stream to cut and mix the in-situ soil with grout. A larger nozzle diameter of 3.0 ~ 4.2 mm is used to allow a larger grouting rate. The standard operating parameters are shown in Table 2. Using these parameters, it can rapidly install a grout pile with a diameter up to 1.6 ~ 3.5 m at a depth up to 50 m below the ground surface.

3.2 Operating Parameter

The pilot test was to confirm the operating parameters required for construction. As Table 2 shown, for $\phi=2.0$ m where jet grout pressure is 32 MPa, jet grout flow is 180 L/min. However, with the difference in the conditions of applying the auxiliary measures of sludge, the parameters will be changed, as the rotation speed is set to be 6-8rpm, and the lift rate then becomes 10-12 min/m. For $\phi=3.2$ m where jet grout pressure is 35 MPa, jet grout flow is 360 L/min. However, with the difference in the conditions of applying the measures of sludge, the parameters will be changed, as rotation speed be 5~6 rpm, lift rate become 12~14 min/m.

Type			R1		R2		
Effective diameter (m)	Sandy soil	$N \leq 50$	2.0	2.5	3.0	3.0	3.5
	Clayey soil	$N \leq 3$					
	Sandy soil	$50 \square N \leq 100$	1.8	2.3	2.7	2.7	3.2
	Clayey soil	$3 \square N \leq 5$					
	Sandy soil	$100 \square N \leq 150$	1.6	2.0	2.4	2.4	2.8
	Sandy soil	$5 \square N \leq 7$					
Grout pressure (MPa)			30 \square 34				
Grout flow rate (L/min)			140	180	260	320	360
Air flow rate (Nm ³ /min)			Over 6			Over 10	
Lift rate (Nm ³ /min)			10	12	12	10	12
Remark: 1. Standard jet grouting depth shall be $0 \square Z \leq 30$ m. In the case of $Z \square 30$ m, effective diameter shall decrease with depth. 2. N value refers to the maximum N value of the subject ground. 3. In the case of gravel, the effective grout column diameter will be 10% less than that of sandy soil in principle. Advance trial grouting for the diameter confirmation is recommended. 4. In the case of higher fine content (high cohesion) in sandy soil, it is possible to carry out the design as cohesive soil. Particularly when the cohesion is above 50kN/m ² , there is a possibility that the designated effective column diameter cannot be reached. 5. The standard mix proportion of grout slurry is 620 kg per 1m ³ . If this mix proportion of grout slurry is changed, a review of lift rate is necessary.							

Table 2: Standard operation parameter (from Rapidjet Association, 2019).

3.3 Pilot Test Construction Procedure

The main procedure is shown in Figure 2. Step 1: Set up the drilling machine to the required position and drill with casing pipes until the designed depth. Step 2: Putting double tube rods into the pre-drilling casing pipes. Step 3: Removing all casing pipes. Step 4: Trial test to check if the parameters are correct or not. Step 5: After pre-jetting, raise the double tube rods automatically to form jet grout columns. Step 6: Removing all rods after jetting work is finished. The construction sequence for the designed pile diameter of 2.0 m and 3.2 m is Type A → Type B → Type C. The lower half of Type B and Type C is first applied with a water jet cutting length of about 4.0 m, followed by 4.0 m high-pressure grouting, after that followed by the first half of the waterjet cutting is about 4.0 m long, and then high-pressure grouting (overlapping 0.5 m) is performed with a length of about 4.5 m.

4. Quality Assurance Method

4.1 Drilling Alignment Measurements

In the jet grouting design, due to the equilateral triangle configuration, all design pile diameters need to overlap within the improved range, so the verticality of the jet hole position will affect the construction quality. The shape acceleration array device (SAAScan) was used to measure the verticality of grouting holes. SAAScan is composed of a series of electromechanical sensors with a length of 50 cm. The sensors are connected in series with flexible joints, which can be customized to any length (Cheng et al, 2020). The measurement accuracy of SAAScan is very accurate ($\pm 1.5 \text{ mm}/32 \text{ m}$), and the outer diameter (23 mm) was sufficiently small to be inserted directly into the drill rod. Thus, the removal of the drill rods was unnecessary when measuring the drill alignment. The photos of the SAAScan device measurement on-site as shown in Figure 3.

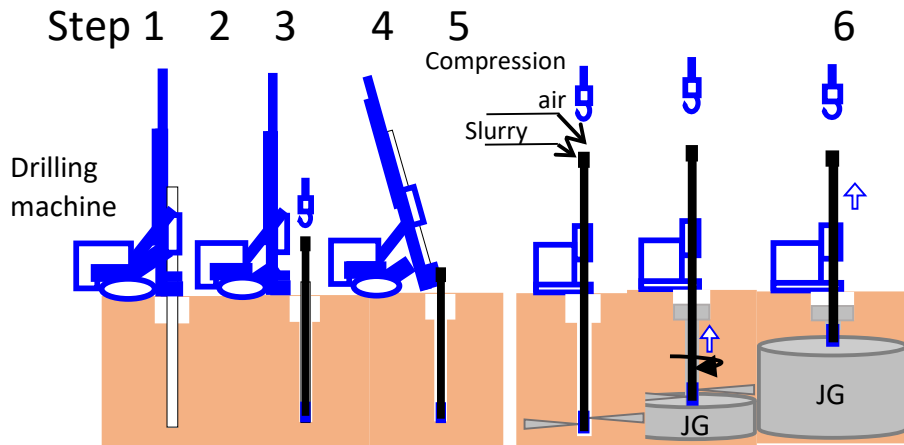


Figure 2: Pilot Test Construction Procedure (Rapidjet Method Jet Grouting Guideline, 2019).



Figure 3: Photos of SAA device measurement on site.

4.2 Jet Wave Monitoring (JWM) Test

In the past, Taiwan has used microphones to collect cutting sound during the jet grouting process to verify the diameter of the formed pile (Fang et al., 2006). There are 3 ~ 4 sounding tubes that were set up near the designed pile diameter (for example 0.8 times, 1.0 times, 1.25 times the design pile diameter), and using the microphones placed in the sound tube to synchronize with the cutting sound. The sound was then collected during jet grouting, and the audio output device was used to determine whether the cutting sound reached the designed pile diameter or not to confirm the effective improvement of the pile diameter. In this study, the Jet Wave Monitor (JWM) system is used to evaluate the effective pile diameter of jet grouting in a qualitative manner (that is, to determine whether the sound tube of the designed pile diameter range has/has received cutting sound). The audio monitoring system mentioned in this study emphasizes that it can digitize the cutting audio generated every 0.1 seconds in the grouting process, and

test pile diameter excavation measurement to confirm its applicability. The audio monitoring system is composed of four parts: audio receiver, steel sound tube, radio device, automatic synchronization lifting device, and data recorder, as shown in Figure 4.

During jet grouting, the sound receiver should be placed at the predetermined grouting depth and raised in synchronization with the grouting rod and nozzle to accurately record the cutting sound at each grouting depth. At the same time, in order to establish a standard sound monitoring program, at least 3 to 4 sound measuring tubes should be set up. It is recommended that at least one be placed within the design pile diameter, one should be above the design pile diameter, and one should be outside the design pile diameter. The material and size of the sound tube used should also be standardized. This test uses seamless steel with an outer diameter of 76.3 mm and a thickness of 4.2 mm. The tube should also be filled with water during installation to reduce noise interference. The gap between the borehole and the sound tube is backfilled with cement-bentonite to ensure the stability of the sound tube (Cheng et al. 2017).

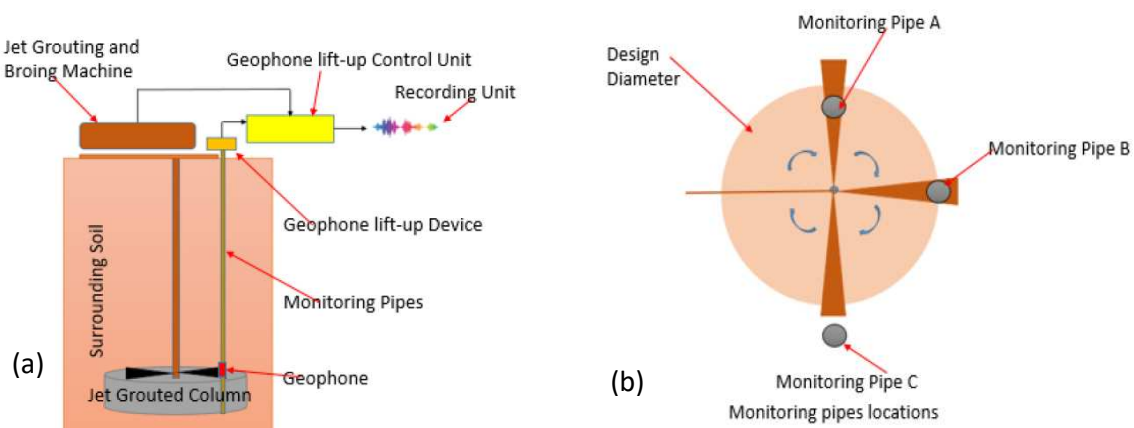


Figure 4: (a) Components of acoustic monitoring system (b) Plan view of monitoring pipe placement.

4.3 In-situ Permeability Tests and Uniaxial Compression Strength Tests

The in-situ permeability test adopts the variable head permeability test. Before the test, install a transparent test tube with a scale, pour water into the test hole until the water level is full to the top of the test tube, and start measuring the drop meter of the water level for 16 minutes. The calculated permeability coefficient (k) must be less than $<1 \times 10^{-5}$ cm/sec. Uniaxial compression strength (UCS) is carried out in the laboratory. In the samples taken by the traditional core-drilling sampling method, the required 28-day strength of clay soil $UCS \geq 10.0$ kgf/cm²).

5. Test Result

5.1 Drilled alignment

When the drilling depth is 16 m, the maximum deviation of the hole bottom shall not be greater than 8 cm. Taking the design diameter $\phi = 2.0$ m as an example, the drilled alignment measured results shown in Figure 5, indicated that the drilling accuracy is slightly less than 1/ 200, which is in line with design requirements. The design overlap of the two grouted columns is equal to 268 mm for a design diameter of 2.0 m, and it can be noted that the actual overlap distance ranges from 248 mm to 300 mm at a depth of 16 m as shown in Figure 6. It is very important to control the vertical grout hole at a great depth of grouting.

5.2 Actuated Formed Pile Diameter

The Jet Wave Monitoring (JWM) sound measuring system records the cutting sound of the jet stream during the jetting process. The minimum value (equivalent to the background value) and the maximum value (peak value) of the cutting sound that is measured at every 25mm can be precisely calculated. The amplitude (maximum value - minimum value) unit is calculated by multiplying the decibel (db) by 10. Figure 7 shows the results of the JWM sound measure recorded. It shows that the Type A amplitude of directly cutting $\phi = 2.0$ m and $\phi = 3.2$ m with grouting material is about 400~600 db x10. The amplitude of Type C cutting with $\phi = 2.0$ m and $\phi = 3.2$ m is about 100~700 db x10 after waterjet cutting and then cutting with grouting material. It can be noted that the

amplitude distribution of Type A is relatively concentrated, while Type C may have disturbed the ground by waterjet cutting, and its amplitude distribution is relatively scattered. Regarding the JWM test, its amplitude has different responses in different formations. In this case, the minimum value of the amplitude is 100 db x10 is used to confirm the size of the jet grout diameter during grouting.

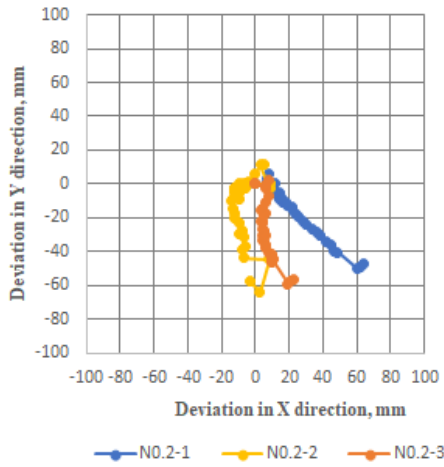


Figure 5: SAAScan vertically test results ($\phi = 2.0$ m).

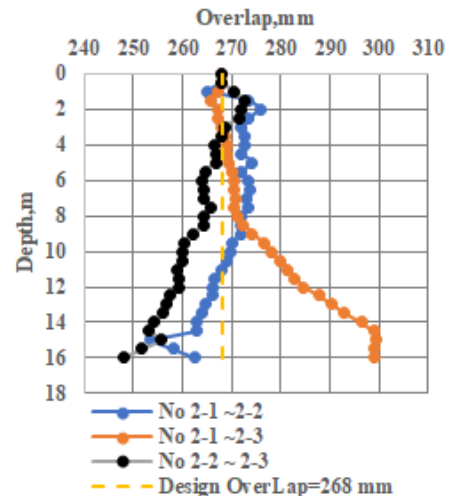


Figure 6: Overlapping results ($\phi = 2.0$ m).

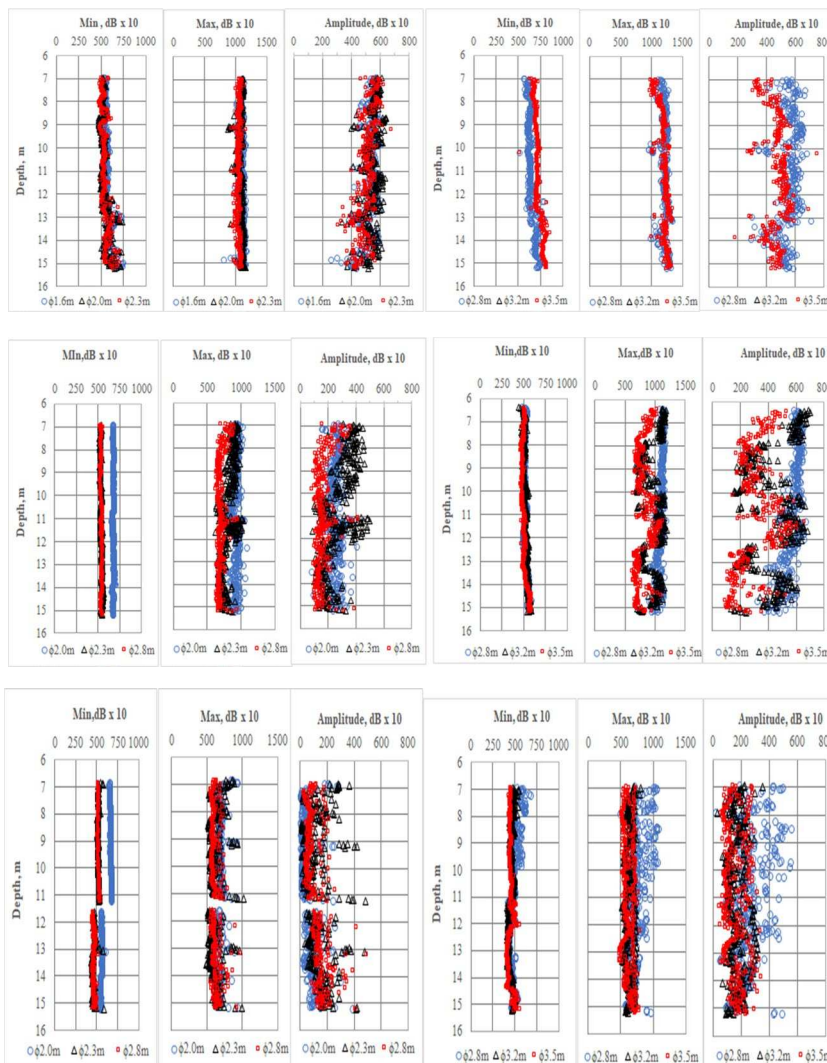


Figure 7: JWM sound recorded.

5.3 Core Sampling Verification

In order to verify the correctness of the JWM results, the traditional method of drilling core sampling is used to sample at the intersection of the three piles. After the sampling is completed, a permeability test is performed to check the coefficient of permeability for the improved zone. The sampling depth is 7.47 m~14.71 m, the sampling length is 7.24 m, the field permeability coefficient k is between $1.19 \times 10^{-6} \sim 1.51 \times 10^{-6}$ cm/sec, the total core recovery is between 92%~99%, and the 28 days of compression strength of the samples is between 23.3~38.1 kgf/cm² as shown in Table 3. The sampling and test results meet the requirements of the test specification.

Test No	Location	Depth, m	q _u , kgf/cm ²
			Top/Middle/Bottom
No.2-T1	3 pile intersection	11.77~12.57	27.9/24.2/23.3
No.2-T2	2/3 radius of pile	12.97~14.97	24.9/38.1/31.7
No.3-T1	3 pile intersection	10.77~12.32	32.8/28.6/34.6
No.3-T2	2/3 radius of pile	13.00~14.40	33.1/29.2/38.0

Table 3: 28 days compression strength.

5.4 Excavation Inspection of Pile Diameter

The diameter of the pile can be verified by the drilling core sampling method. The diameter of the pile can also be confirmed by direct excavation inspection. In these pilot tests, once the grouting operation is completed, the Type C test is selected in the shallow overburden area near the bottom of the sludge pit. The pile is then sprayed with a thickness of about 50 cm of the improved pile outcrop according to its operating parameters, and the excavation of the improved pile outcrop and the actual forming size are measured after the core sampling and in-situ permeability test. Figure 8 shows the measurement results of pile diameters 2.0 m and 3.2 m. The actual forming pile diameter with the design pile diameter of 2.0 m and 3.2 m are approximately 2.3 m, and 3.3 m respectively, and both of them meet the requirements of the design pile diameter.



(a) Exposed of Jet Grouting column $\phi=2.0$ m



(b) Exposed of Jet Grouting column $\phi=3.2$ m

Figure 8: Exposed of Jet grouting and inspection of pile diameter.

5.5 Sludge Discharge by Different Measures

Table 4 shows the comparison of the specific gravity of sludge by various measures. It can be noted that different measures for sludge discharge, can reduce the specific gravity of sludge. When the specific gravity of sludge decreases, its fluency increases and reduces the occurrence of failure due to block of discharge sludge, which results in the pressure being unable to vent, causing the surrounding roads to uplift or overflow. Using water jet cutting and release holes, the sludge drainage effect is indeed improved. The monitoring results of the design pile diameter are 2.0 m in Type A, B, and C. The three construction methods during the grouting process of each meter are shown in Figure 9. It can be observed that the specific gravity in hole No. 2-3 (Type C) is significantly lower than the other two types of construction methods under the condition of water per cutting and additional release holes.

The pilot test also uses the data-logger method to record the grouting parameters during the construction period as shown in Table 5. In addition to QA/QC of the construction status, the relevant record data can also be used as useful reference information for construction quality control.

Pile No	No. 2-1	No. 2-2	No. 2-3	No. 3-1	No. 3-2	No. 3-3
Construction type	Type A	Type B	Type C	Type A	Type B	Type C
Waterjet cutting		v	v		v	v
Setting of the sludge discharge hole			v			v
Specific gravity of sludge, t/m ³						
Max.	1.78	1.64	1.63	1.76	1.64	1.59
Min.	1.50	1.51	1.44	1.48	1.53	1.44
Ave.	1.71	1.59	1.56	1.63	1.57	1.54

Table 4: Comparison of the specific gravity of sludge by various auxiliary measures.

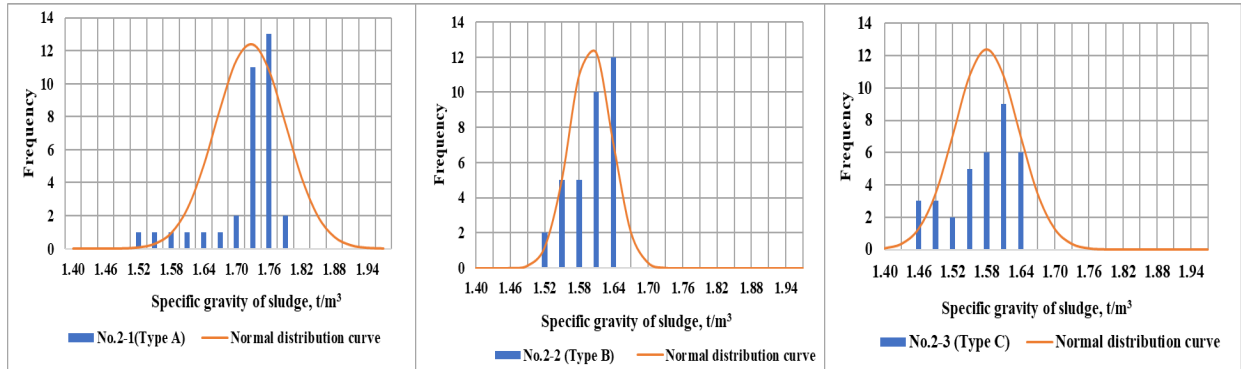


Figure 9: The distribution of the specific gravity of sludge in Type A, B, C three methods.

Item	Water/Slurry	Depth(m)	Pressure (MPa)	Flow (L/min)	Lift rate (min/m)	Rotation(RPM)
(A) Design pile diameter $\phi=2.0$ m						
No.2-1	Slurry	6.91~15.21	NG	179.22	9.69	6.80
No. 2-2	Water	11.18~15.21	NG	99.00	5.60	7.09
	Slurry	11.18~15.21	NG	182.98	9.84	6.99
	Water	6.96~11.36	NG	120.00	5.59	7.02
	Slurry	6.80~11.63	NG	179.87	9.60	7.06
No. 2-3	Water	11.16~15.21	12.26	120.00	4.97	7.58
	Slurry	11.21~15.26	30.69	173.51	9.58	8.16
	Water	6.94~15.26	12.19	124.00	4.74	9.37
	Slurry	6.91~11.71	29.53	168.99	9.72	8.19
(B) Design pile diameter $\phi=3.2$ m						
No.3-1	Slurry	6.96~15.21	34.33	355.37	13.65	4.22
No. 3-2	Water	11.21~15.21	26.47	356.80	7.04	5.00
	Slurry	11.21~15.21	34.56	356.49	13.66	4.24
	Water	7.21~11.21	8.55	210.37	6.66	5.01
	Slurry	6.99~11.74	34.50	355.54	13.66	4.17
No. 3-3	Water	11.21~15.21	10.17	221.23	6.65	4.65
	Slurry	11.21~15.21	34.74	358.32	11.57	4.19
	Water	6.94~11.21	12.99	258.30	6.62	4.68
	Slurry	6.94~11.71	34.80	354.41	11.62	4.25

Table 5: Jet grout datallogger recorded.

6. Conclusions

- (1) Using the Jet Wave Monitoring (JWM) system, the most suitable grouting parameters can be obtained during the pilot test and can be adjusted the grouting parameters during the jet grouting process, which is

different from the traditional verification of the pile diameter, which requires waiting for 28 days sampling, which can be greatly reduced test duration.

- (2) SAAScan verticality inspection can improve the management of construction quality accuracy to meet the design requirements, and the inspection method is relatively rapid, due to the advances in application technology in engineering.
- (3) The soil condition, in this case, is a soft clay layer, and by using the Type C method (waterjet per cut + release hole +extend sludge discharge path), the sludge can freely flow to the surface.

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