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Quality control of double fluid jet grouting below groundwater table: Case history

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Abstract

A jet grout block created by overlapping columns aimed to convert the saturated silty sand soils into a safe space for breaking down four underground parking uplift piles along the tunnel alignment. Since the grouting platform was located on the mat foundation in the basement of underground parking and was under the groundwater table, a series of dewatering wells were installed before the 177 columns were constructed to prevent intrusion of the groundwater flowing upward from sandy soil to basement through grouting hole during wash boring and grouting stages from happening. Several quality control measures were undertaken prior to quality assurance testing. Two measurements of spoil return and spoil flow rate for each column were implemented. From a back analysis from the mean values of spoil density and spoil flow rate, the column diameter was estimated at around 1.56 m, slightly smaller than the design diameter by 2.5%. In addition, a control chart with upper and lower control limits, established from a large dataset of flow rate of spoil return, was a means to recognize the likelihood of sand boiling and to serve as an early warning indicator of abnormal conditions for the jet grouting works below the groundwater table. As the mean spoil density of the infill column was larger than perimeter column, an optimal grouting sequence for clusters was suggested in this paper. The jet grout block exposed during the breakdown process of the piles showed safe working conditions as required and a shield machine then passed through as planned.
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Keywords: Double fluid jet grouting; Spoil density; Spoil flow rate; Column diameter; Infill column

1. Introduction

There are three jet grouting systems to choose from: a single, double, and triple system. The single system injects grout only at high pressure. This was the first system to be used: the resulting column diameter is limited and the boreholes sometimes become jammed, resulting in ground heave (Croce and Flora, 1998). The column sizes are small, usually less than 1 m in diameter.

The JSG (Jumbo-jet Special Grout) method is a jet grouting method with two fluids, neat cement grout and air (Yahiro et al., 1982; Miki and Nakanishi, 1984). The cement grout is injected at high pressure and is aided by a cone of compressed air, which shrouds the grout injection. The air reduces the friction loss, allowing the cement grout to travel further from the injection point, thereby producing larger column diameters. The addition of the air shroud increases jetting efficiency

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dramatically, typically resulting in an increase of 30% or in the design diameter for the same jetting energy. Nevertheless, the presence of the air bubbles means that that the column is not as strong as those produced by the single-fluid method, and more spoil return is produced.

The triple system differs from the single and double systems in that the erosion of the ground is carried out by a high pressure water jet shrouded with air and the eroded region is replaced by cement grout with an additional low pressure grout line. The single and double fluids are in-situ mixing methods, not soil replacement methods like the triple fluid method.

As mentioned above, the double fluid jet grouting technique results in the partial replacement of in-situ soil within the grouted column, thereby improving strength and reducing permeability. Because the overlap of the column with previously constructed columns can be accurately controlled, low permeability can be secured, thus avoiding the risk of leakage of water or soil through the gap between jetted columns. The accuracy of any quality control technique to evaluate the actual diameter of jet grout column is thus of major concern to the grouting industry.

The jet grouting diameter is affected by soil properties and jet grouting parameters (the lifting speed and rotation frequency of the monitor, the grout volume, the grout pressure, and the nozzle diameter) (Malinin et al., 2010). Therefore, these parameters are required for manually monitoring and for the automatic data acquisition system. However, either of these procedures provide solid values with regard to improved strength and the diameter of jet column. Quality assurance (Wang et al., 2013) is therefore generally adopted by sampling grout cubes and spoil cubes and performing breaks on both, along with taking spoil density readings throughout the jet grouting process to check the strength compatibility with the trial test sections (Langhorst et al., 2007; Hurley, 2005; Stark et al., 2009). Similarly, Kauschinger et al. (1992) developed mass balance equations for the single fluid jet grout system, which can be adopted to estimate the size and composition (soil, water, and cement) of spoil and soilcrete (jet grout column) by measuring the densities of soilcrete, cement grout, and spoil.

Hydrophones were used by Langhorst et al. (2007) and Hurley (2005) to detect the vibrations in the tubes at defined radii during the trial grouting program. This gave qualitative indications that the desired column diameter was being achieved which, when combined with a back analysis of spoil return densities, provided the confidence to proceed with production work. However, the installation of tubes for hydrophones is costly and time consuming. This will limit hydrophone method only to trial grouting programs, and makes it impractical for quality control during production work using the jet grout column.

Langhorst et al. (2007) and Malinin et al. (2010) used an innovative measuring device which was made of two crossing bars moving apart against the wall of the column wall before the grout set. Although the measured diameters of the columns were well-matched with those observed from the exposed columns after excavation, this device is not effective with jet columns at greater depths. In addition, Ho (2011) used an analytical model to predict the cutting distance of air-shrouded jets in cohesive soil. The model variables were calibrated by back-analyzing jet grouting field trial results at a nearby site with similar soil conditions.

Flora et al. (2012) proposed a most promising jet grouting design method by conducting a statistical analysis to obtain the mean value and coefficient of variation of the column diameter and verticality based on the measured values from a jet-grouting field trial. Then the uplift safety factor of the water sealing barrier made by jet grouting at the bottom of open excavation (Croce and Flora, 2000; Croce and Modoni, 2007; Flora et al., 2007; Lignola et al., 2008; Modoni et al., 2006) was estimated by the Monte Carlo procedure by assuming the column diameter, column spacing, and a given risk level. This method is quite simple and also accurate, and is ideal for use as a quality control method for production work.

This study presents a case history where a double fluid jet grouting project was conducted to maintain safety when four underground parking uplift piles were broken (Xu et al., 2014) during subway tunnel construction. Since the grouting platform was below the groundwater table, there was a possibility that groundwater would flow upward from the sandy soil to the basement through the grouting hole during the wash boring and grouting stages. Such leakage may have led to a serious incident, such as sand boiling. Therefore, two measurements were taken: spoil return and the spoil flow rate for the soilcrete column. A back analysis from the mean values of spoil density and spoil flow rate was utilized to estimate the column diameter. A control chart with upper and lower limits was developed in this paper to provide an early warning indicator of water leakage from a sand boiling issue. Apart from that, an optimal grouting sequence in a cluster was suggested in this paper in order to have more infill columns than perimeter columns.

2. Site characterization

Two 6.5-m diameter bored parallel tunnels driven using Earth Pressure Balance (EPB) shields need to pass beneath an existing underground parking under where four uplift piles, indicated by the red circle in Fig. 1, are in the way of the alignment. Double fluid jet grouting at depths ranging from 23.27 to 34.91 m was undertaken to improve the strength and reduce the permeability of the silty sand layer below the mat foundation of the underground parking. The purpose of this exercise is to provide a safe place for excavating the soils around the piles and then removing these piles from the alignment (Figs. 1 and 2). To prevent substantial structure heaves or settlements from occurring during jet grouting, real-time monitoring was implemented using electronic beam sensors installed in the underground parking (Fig. 1).

As seen in Fig. 2, the soil succession at this construction site of Taipei City comprises a fill of about 1.35-m in thickness, sitting on a 2.9-m thick medium stiff silty clay underlain by 11.15-m thick loose silty sand then 7.35-m thick medium stiff silty clay which extends to a thick layer of medium dense silty

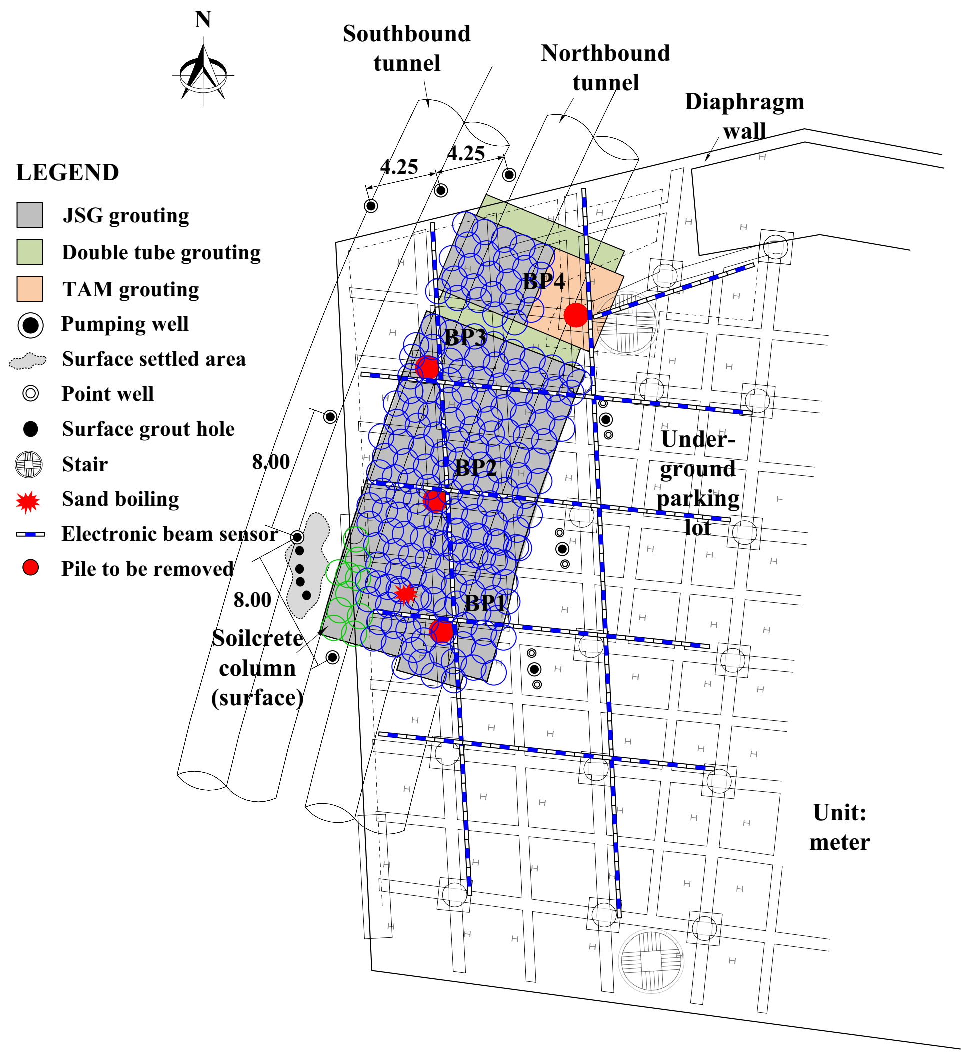

Fig. 1. Plan view of the four piles in way of tunneling.

sand, followed by a gravel formation. The water table of this 11.15-m thick silty sand layer is some 4.25 m below the surface and the water table of the thick lower silty sand layer, with a thickness of 19.25 m, is 6.7 m deep.

Since the top sand layer under the mat foundation was laterally enclosed by a diaphragm wall and underlaid by an impermeable clay layer, it was presumed that the groundwater of this sand layer within this confined region was hydraulically cut off from the same soil layer outside (Fig. 2). Therefore, the groundwater in this top sand layer would not flow into the basement through grouting holes unless there were water seepage paths in diaphragm wall. Nevertheless, because it was possible that the groundwater level in the bottom sand layer, which was higher than the grouting platform, could flow into the basement through grouting holes, a dewatering system was installed before the grouting holes were drilled. To avoid possible surface settlement and building tilting outside the diaphragm wall due to the lowering of the groundwater level, dewatering wells were installed to the right of the grouting area, far away from the diaphragm wall. A total of six point wells and three pumping wells were deployed evenly into three pits, as shown in Fig. 1. The point wells were opened to lower the groundwater level in the top sand layer to just below the mat foundation and the pumping wells were then opened to maintain the groundwater level in the bottom sand layer at a similar level.

3. Jet grouting work

A total of 187 jet columns1.6 m in diameter were constructed to provide a safe working space for breaking down the uplift piles inside the jet grout block with a minimum unconfined compressive strength of 2 MN/m^2 for sandy soils or 1 MN/m^2 for clayey soils and a permeability of less than 1×10^{-7} m/s. A 1000 l grout mix consisting of 120 kg of type 1 Portland cement with a specific gravity of 3.15, 280 kg of fly ash with a specific gravity of 2.86, and 864 kg of water provided a density of 1.264×10^3 kg/m^3 of cement-based grout to be used for double fluid jet grouting.

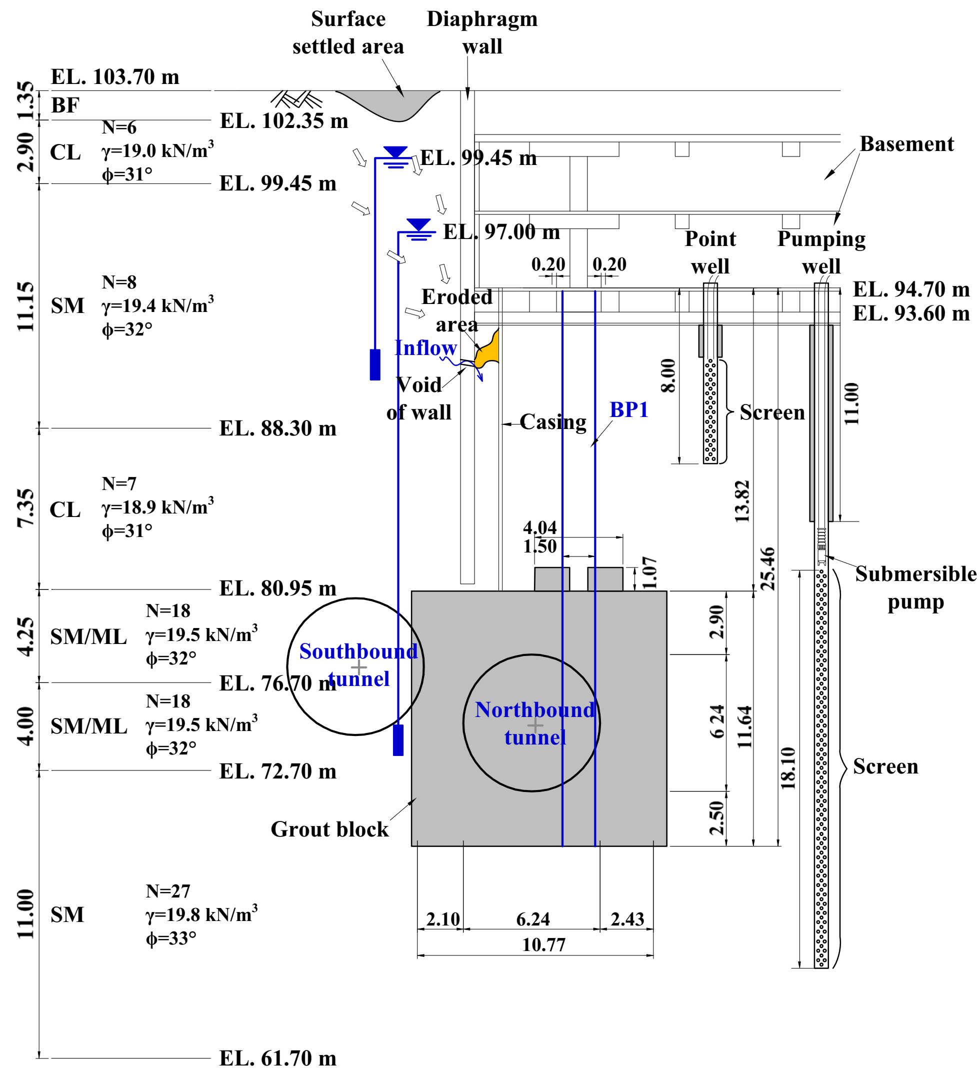

Fig. 2. Subsurface profile along with grout block and construction details of the wells.

As shown in Fig. 1, 177 columns were installed from the mat foundation floor within this underground parking structure and 10 columns, marked by the green circle, were installed at the ground surface outside the structure. Due to the constraint of the working area imposed by the presence of existing beams and columns on the mat foundation, jet grout holes were drilled from within pits surrounded by beams. While most columns were drilled vertically, for some columns, the drilling inclination was up to 20 degrees from the vertical. At each grouting pit, a cluster of 13 to 15 columns were constructed to form overlapping grout columns, as shown in Fig. 1.

At each column position, a borehole was first drilled to the design depth and then the jetting monitor was withdrawn at a speed of 30 min/m and rotated with a speed of 6 to 8 rpm, while cement grout was grouted under pressure of 20 MN/m^2 through the nozzle of 2.8 mm in diameter at 0.06 m^3/min and an air flow of 0.06 m^3/min was injected around the jet grout with a pressure of 0.7 MN/m^2. The pressure and flow rate of the jetting fluids was sufficient to erode the soil and to mix it. Pressurized air was used not only to conserve the energy of jet grout, but also to provide soil lift. The jetting parameters summarized in Table 1 are justified by the design chart of Japanese Jet Grouting Association (JJGA, 2002) based on the soil type, the SPT blow count, and depth, and were adopted for the production grouting work in this project.

Table 1
Jet grouting parameters for production work.

Air pressure (MN/m^2)	0.7
Air flow rate (l/min)	1500
Grout pressure (MN/m^2)	20 ± 2
Grout flow rate (l/min)	60
Withdrawal rate (min/m)	30
Rotation speed (rpm)	6 to 8
Water–cement ratio	2.16

4. Volume and density measurements of spoil return

The jet-grouting spoil was discharged through annulus between drilling rod and pipe. In this project, the spoil was

Table 2
Ratio of the spoil volume to the grout volume for a unit length of column.

Column no.	Measured section (from tip)	Ratio
Machine no.1		
4	1	1.49
	8	1.37
5	1	1.82
	2	1.62
	3	1.43
	9	1.37
18	2	1.37
	5	1.40
24	2	1.22
	8	1.06
23	1	1.77
	2	1.38
	5	1.24
22	1	1.67
	2	1.34
	8	1.24
21	1	1.92
	2	1.52
	9	0.86
	10	1.38
8	1	1.56
	2	1.33
	8	1.37
9	2	1.37
	8	1.37
10	1	0.93
	9	1.01
14	1	1.06
	8	1.06
15	2	1.62
	9	1.47
19	1	1.01
	9	1.17
20	1	1.17
	8	1.22
25	2	1.11
	8	1.39
28	2	1.11
	7	1.01
29	2	1.47
	9	1.42
30	1	1.62
	2	1.40
	7	1.29
31	1	1.17
	8	1.22
32	2	1.26
	7	1.22
33	2	1.82
	3	1.37
	7	1.17
34	2	1.62
	3	1.30
	8	1.22
35	2	1.87
	3	1.45
	6	1.26
36	3	1.47
	8	1.37
37	2	1.06
	6	1.37
38	2	1.56
	3	1.39
	7	1.47
39	2	1.22
	8	1.77
	9	1.41
44	1	0.97
	8	1.37
46	1	1.17
	7	0.91
55	4	0.97
	9	1.31
65	2	1.26
	6	1.23
66	2	1.01
	9	1.46
	Avg.	1.33
Machine no.2		
43	1	1.22
	9	1.47
51	2	1.01
	8	1.22
59	4	1.31
	8	1.37
60	2	0.86
	3	1.24
	8	1.11
67	3	1.11
	9	1.11
68	3	1.22
	7	1.47
70	2	0.91
	3	1.39
	8	1.22
71	1	1.26
	8	1.26
73	2	1.06
	7	1.37
76	3	1.11
	8	1.42
77	1	1.17
	8	1.11
78	2	1.22
	7	1.11
79	2	1.01
	8	1.06
80	1	1.11
	9	1.22
97	2	0.99
	9	1.17
89	1	1.37
	10	1.77
88	1	1.44
	8	1.22
84	2	1.67
	4	1.41
	9	1.29
85	3	1.52
	9	1.11
86	2	1.22
	9	1.17
87	3	1.77
	4	1.40

Table 2 (*continued*)

Column no.	Measured section (from tip)	Ratio
	9	1.37
93	1	1.22
	8	1.24
94	2	1.13
	10	1.01
95	2	1.06
	8	1.37
96	1	1.92
	2	1.43
	8	1.42
102	3	1.37
	7	1.42
103	2	1.06
	8	0.86
	9	1.19
104	2	1.22
	8	1.26
105	2	1.26
	8	1.72
	9	1.42
106	2	1.06
	8	1.11
113	2	1.13
	7	1.09
122	1	1.19
	2	1.11
	Avg.	1.25
Machine no. 3		
130	3	1.06
	10	1.52
137	4	1.62
	5	1.34
	8	1.37
138	2	1.47
	8	1.31
139	4	1.62
	5	1.34
	10	1.37
145	1	1.52
	3	1.43
	10	1.06
146	3	1.37
	7	1.31
147	3	1.37
	9	1.31
148	3	1.52
	4	1.40
	10	1.22
155	1	1.87
	2	1.44
	8	1.37
156	2	1.26
	9	1.37
157	4	1.11
	8	1.13
163	1	0.86
	3	1.18
	9	1.17
164	3	1.22
	8	1.37
165	2	1.72
	3	1.39
	8	1.22
166	4	1.11
	9	1.22
174	3	1.37
	7	1.31
175	3	1.47
	8	1.31
181	2	1.31
	8	1.29
182	3	1.26
	9	1.42
183	2	1.28
	7	1.23
187	2	1.17
	9	1.17
	Avg.	1.33
	Summary	
Machine no.	Avg. ratio	
Machine 1	1.33	
Machine 2	1.25	
Machine 3	1.33	
Total avg.	1.30	

collected in a confined temporary holding space and then conveyed to a pit of 3.79 m (L) by 2.40 m (W) by 1.25 m (H) where the spoil volume was measured before it was pumped to the ground surface to be shipped out. The density of spoil returns sampled from the grout hole was also measured using the mud balance along with the measurement of spoil flow volume at 1 m intervals of during jet grouting. To ensure their validity, measurements were taken twice for each column, one 2 to 4 m from the column tip and the other 7 to 11 m from the column tip.

5. Volume measurement of spoil return

As cement grout is jetted into saturated in-situ soil to create a mixture of grout and soil, some remains in the ground to form a jet grout column and some flows to the surface. The soil which returns to the surface is referred to as spoil return. According to the theory of mass balance, the volume of jetted grout should be equal to the volume of spoil return (mixture flowing to the ground surface). However, in reality the volume of spoil return is larger than the volume of jetted grout, and the amount of depends on the soil type, such as clay or sand. The design value of the volume ratio of spoil to grout is suggested by JJGA is 1.3 when using clayey soil, and 1.1 for sandy soil. Since the grouted area in this construction site consists of silty sand mixed with layers of silty clay, the average volume ratio, calculated by the spoil return volume divided by the grout volume for 1 m long column, was expected to be in the 1.1 to 1.3 range. The grout volume injected during 30 min of lift for a 1 m long column with an injection rate of 60 l/min is 1.8 m^3, and the spoil volume is measured in a pit with known length and width dimensions. The ratios of spoil returns to grout volumes measured for a unit length of columns are summarized in Table 2 and can be also presented as a control chart in the order of production sequence, as shown in Fig. 3.

With a mean value of 1.302, the upper control limit (mean value plus 3 times the standard deviation) and lower control limit (mean value minus 3 times the standard deviation) are determined to have been 1.970 and 0.634, respectively. This slightly higher mean value of 1.302, not between 1.1 and 1.3 for silty sand mixed with layers of silty clay suggested by JJGA, could be caused primarily by the addition of groundwater into spoil as grouting platform is below groundwater table. The other possible cause may be the expansion of soil particles due to the effective stress relief of in-situ soil under

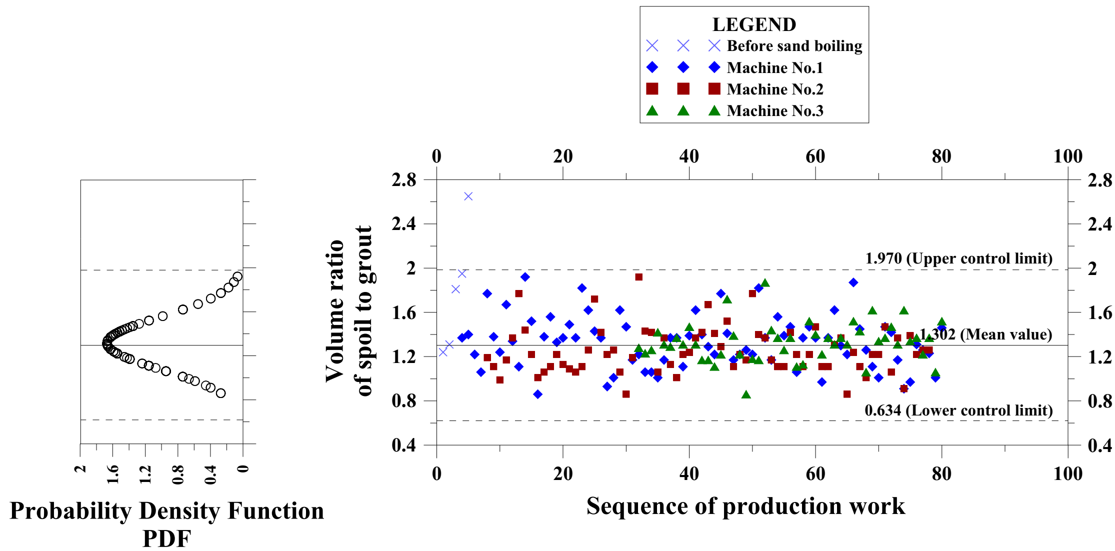

Fig. 3. Control chart of the volume ratio between the spoil return and grout.

Fig. 4. (a) Photo of a pit near diaphragm wall before sand boiling, (b) a hole left by withdrawing intermediate pile in the pit, and (c) sand boiling in a pit next to the grouting pit.

Fig. 5. (a and b) Pits flooded with boiling sand and (c) a surface settled area.

underground parking. Any possible random errors from measurement should be dealt with statistical analysis.

According to the Western Electric Company (1956), a process is considered out of control if the following criterion is met: Two of the three most recent points plot outside and on the same side as one of the 2-sigma control limits. Juran (2010) also proposes the same criteria. The chance that two out of three points in a row fall outside the warning limit is only about 1%. In Fig. 3, the volume ratios of spoil to grout for the first five columns were 1.24, 1.31, 1.81, 1.95, and 2.65 shown by cross points. The three most recent ratios are bigger than the 2-sigma control limit (mean value plus 3 times standard deviation), which is 1.746. At this time, sand boiling (Fig. 4c) from a hole in the pit was observed where jet grouting near diaphragm wall (Figs. 1, 4a and b) was conducting. It is believed that this square hole was the space left out unfilled after the basement structure was completed and intermediate piles were withdrawn along with bracing system in the past. The flow path of spoil return eroded the soils away between the hole in the pit and the opening on diaphragm wall (Fig. 2) which was caused by inadequate concreting (Ni and Cheng, 2012). The groundwater started to flow through the opening from outside the diaphragm wall because the water level was higher than the grouting pit. This resulted in an increase in the volume ratios of spoil to grout for the first five columns and ultimately triggered the sand boiling (Fig. 5a and b) for several minutes and an extensive surface settled area outside the diaphragm wall, as shown in Figs. 1, 2 and 5c, until the water levels on both sides of wall were equalized.

It is obvious that a control chart with upper and lower control limits established from a large r dataset of flow rate of spoil return along with proper decision-making criteria would provide a way to identify the potential of sand boiling and would serve as an early warning indicator of abnormal conditions for the jet grouting works below the groundwater table. In addition, sand boiling events may be avoided by installing casing from the surface in the pit to the top elevation of the jet grout column (Fig. 2) before jetting as was recommended by Ho (2011). This not only would keep the spoil flow path free from potential blockage, but also eliminate the possibilities of soil erosion and/or sand boiling.

6. Density measurement of spoil return

The densities of spoil returns defined as the weights per unit volume of spoil returns and measured for a unit length of column are listed in Table 3 and are also plotted as a control chart in the order of production sequence, as shown in Fig. 6. The mean value is 1.409×10^3 kg/m^3, and the upper control limit and lower control limit are 1.585×10^3 kg/m^3 and 1.232×10^3 kg/m^3, respectively. The values of standard deviation and coefficient of variation are 0.059 and 0.001, respectively.

In an ideal situation, if the jet grout mixes completely with the in-situ silty sands with several layers of silty clay (Croce and Flora, 2000), then the composition in the jet grout column and in the spoil return should be the same. Due to the effect of bleeding and consolidation, the column density should eventually be larger than the spoil density. Hurley (2005) proposed a quality assurance principle by sampling grout cubes and spoil cubes and performing breaks on both, along with taking spoil density readings throughout each jet grout lift to measure compatibility with the trial test sections.

Herein, the question is how the spoil density is related to the column diameter. Field borehole loggings indicated the average density of in-situ soil is 1.95×10^3 kg/m^3, which is larger than that of grout; that is, 1.264×10^3 kg/m^3 (Table 4). Therefore, the density of the spoil should be in the range of 1.95×10^3 kg/m^3 and 1.264×10^3 kg/m^3. If more in-situ soils are eroded and mixed with cement grout to form a jet grout column, the density of the spoil return should be on the high end. Otherwise, the density of spoil will be lower if the spoil return volume is bigger than the jet grout volume. With this relationship between the spoil density and spoil return volume in mind, the following section will present a simple method to estimate the column diameter by means of a back analysis from the mean values of the spoil density and spoil flow rate.

7. Estimation of column diameter

Spoil densities of column diameters ranging from 1 to 2.6 m with 1 m long are listed in Table 4, where the total weights of

Table 3
Density of the spoil return.

Column no.	Density of spoil (10^3 kg/m^3) Top	Bottom
4	1.45	1.48
5	1.39	1.40
8	1.40	1.37
9	1.47	1.43
10	1.37	1.40
14	1.40	1.37
15	1.36	1.40
18	1.40	1.41
19	1.49	1.49
20	1.34	1.44
21	1.40	1.30
22	1.43	1.36
23	1.36	1.32
34	1.36	1.44
35	1.45	1.28
36	1.37	1.49
37	1.30	1.31
38	1.35	1.28
39	1.48	1.37
43	1.34	1.41
44	1.47	1.37
46	1.56	1.34
51	1.62	1.48
55	1.37	1.43
59	1.40	1.39
60	1.56	1.39
77	1.39	1.38
78	1.52	1.49
79	1.48	1.53
80	1.42	

Table 3 (*continued*)

Column no.	Density of spoil (10^3 kg/m^3) Top Bottom
	1.37
84	1.41
	1.43
85	1.59
	1.51
86	1.44
	1.52
87	1.43
	1.34
88	1.52
	1.40
89	1.46
	1.32
93	1.34
	1.39
94	1.46
	1.49
95	1.49
	1.47
137	1.42
	1.39
138	1.42
	1.32
139	1.46
	1.45
145	1.42
	1.41
146	1.38
	1.39
147	1.37
	1.34
148	1.36
	1.40
155	1.33
	1.28
156	1.42
	1.33
157	1.36
	1.42
163	1.41
	1.43
164	1.47
	1.44
165	1.44
	1.42
24	1.51
	1.47
25	1.42
	1.31
26	1.42
	1.29
27	1.37
	1.52
28	1.45
	1.39
29	1.42
	1.39
30	1.41
	1.34
31	1.36
	1.41
33	1.40
	1.40
65	1.29
	1.31
66	1.52
	1.42
67	1.36
	1.34
68	1.42
	1.42
69	1.44
	1.34
70	1.32
	1.46
71	1.32
	1.36
73	1.37
	1.44
76	1.42
	1.38
96	1.56
	1.50
97	1.38
	1.30
102	1.44
	1.39
103	1.42
	1.45
104	1.38
	1.36
105	1.41
	1.47
106	1.41
	1.43
113	1.38
	1.30
130	1.36
	1.40
166	1.32
	1.36
174	1.32
	1.36
175	1.43
	1.39
181	1.41
	1.37
182	1.44
	1.50
183	1.37
	1.40
187	1.52
	1.43
Avg.	1.41

the in-situ soil with the same volume of jet grout column and cement grout are divided by the total volumes of the jet grout column and the cement grout if the jetted grout is thoroughly

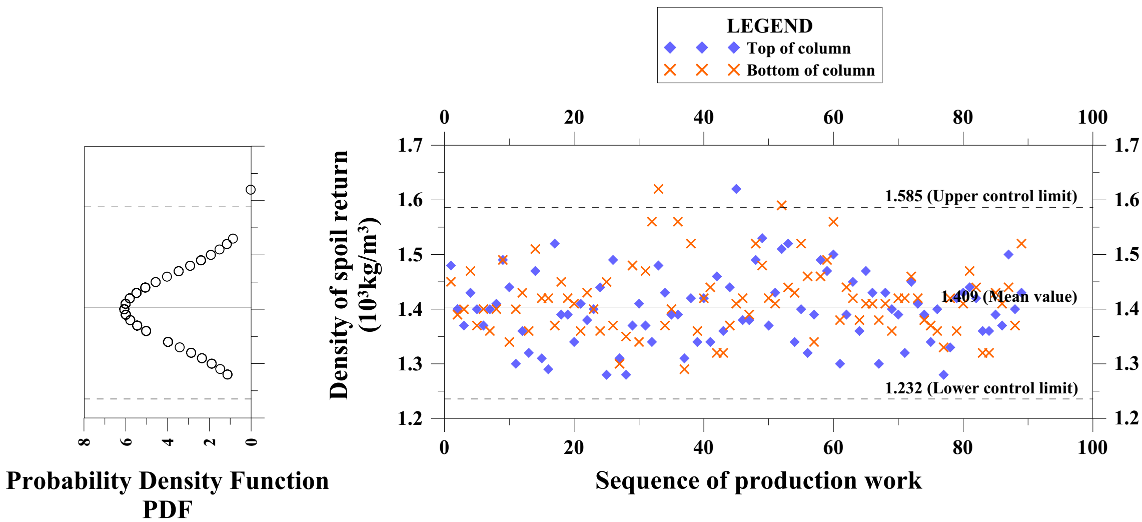

Fig. 6. Control chart of the density of the spoil return.

Table 4
Variation of the spoil density and column diameter.

Column diameter (m)	Height (m)	Column volume (m^3)	In-situ soil density (10^3 kg/m^3)	Grout volume (m^3)	Grout density (10^3 kg/m^3)	Spoil density (10^3 kg/m^3)	Adjust factor	Adjusted spoil density (10^3 kg/m^3)
1	1	0.79	1.95	1.8	1.264	1.47	1.210	1.217
1.1	1	0.95	1.95	1.8	1.264	1.50	1.198	1.253
1.2	1	1.13	1.95	1.8	1.264	1.53	1.186	1.289
1.3	1	1.33	1.95	1.8	1.264	1.56	1.174	1.325
1.4	1	1.54	1.95	1.8	1.264	1.58	1.163	1.359
1.5	1	1.77	1.95	1.8	1.264	1.60	1.152	1.392
1.6	1	2.01	1.95	1.8	1.264	1.63	1.143	1.422
1.7	1	2.27	1.95	1.8	1.264	1.65	1.134	1.452
1.8	1	2.54	1.95	1.8	1.264	1.67	1.125	1.481
1.9	1	2.83	1.95	1.8	1.264	1.68	1.117	1.507
2.0	1	3.14	1.95	1.8	1.264	1.70	1.110	1.532
2.1	1	3.46	1.95	1.8	1.264	1.72	1.103	1.555
2.2	1	3.80	1.95	1.8	1.264	1.73	1.097	1.577
2.3	1	4.15	1.95	1.8	1.264	1.74	1.091	1.597
2.4	1	4.52	1.95	1.8	1.264	1.75	1.086	1.616
2.5	1	4.91	1.95	1.8	1.264	1.77	1.081	1.634
2.6	1	5.31	1.95	1.8	1.264	1.78	1.061	1.674

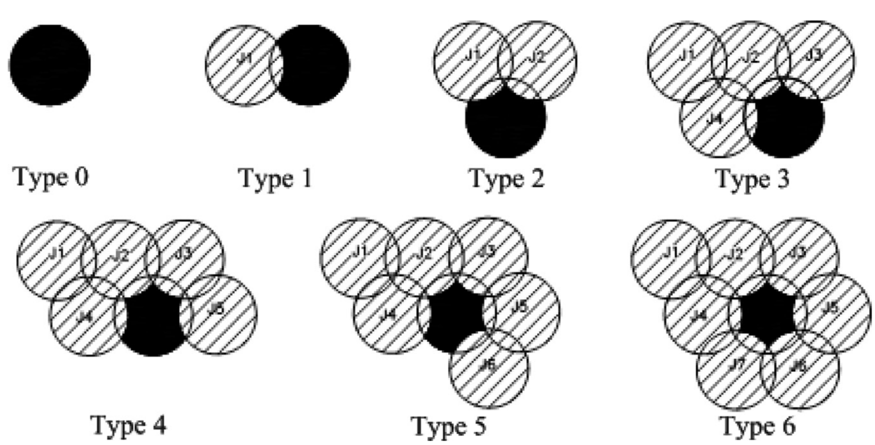

Fig. 7. Types of the overlapping columns.

Table 5
Variation of the volume ratio of spoil to grout and the spoil density due to overlapping types.

Column no.	Ratio of spoil return to grout	Density of spoil return (10^3 kg/m^3)
Type 0		
30	1.62	1.34
	1.40	
	1.29	1.41
34	1.62	1.44
	1.30	
	1.22	1.36
55	0.97	1.43
	1.31	1.37
65	1.26	1.31
	1.23	1.29
106	1.06	1.43
	1.11	1.41
163	0.86	1.43
	1.18	
	1.17	1.41
183	1.28	1.40
	1.23	1.37
Avg.	1.24	1.39
Type 1		
5	1.82	1.40
	1.62	
	1.43	
	1.37	1.39
10	0.93	1.40
	1.01	1.37
15	1.62	1.40
	1.47	1.36
18	1.37	1.41
	1.40	1.40
20	1.17	1.44
	1.22	1.34
32	1.26	1.38
	1.22	1.43
33	1.82	1.40
	1.37	
	1.17	1.40
36	1.47	1.49
	1.37	1.37
37	1.06	1.31
	1.37	1.30
39	1.22	1.37
	1.77	
	1.41	1.48
44	0.97	1.37
	1.37	1.47
66	1.01	1.42
	1.46	1.52
67	1.11	1.34
	1.11	1.36
77	1.17	1.38
	1.11	1.39
84	1.67	1.43
	1.41	
	1.29	1.41
89	1.37	1.32
	1.77	1.46
93	1.22	1.39
	1.24	1.34
97	0.99	1.30

Table 5 (*continued*)

Column no.	Ratio of spoil return to grout	Density of spoil return (10^3 kg/m^3)
	1.17	1.38
103	1.06	1.45
	0.86	1.42
	1.19	
104	1.22	1.36
	1.26	1.38
113	1.13	1.30
	1.09	1.38
122	1.19	1.43
	1.11	1.41
148	1.52	1.40
	1.40	
	1.22	1.36
155	1.87	1.42
	1.44	
	1.37	1.28
166	1.11	1.36
	1.22	1.32
174	1.37	1.36
	1.31	1.32
181	1.31	1.37
	1.29	1.41
182	1.26	1.50
	1.42	1.44
Avg.	1.31	1.39
Type 2		
4	1.49	1.48
	1.37	1.45
21	1.92	1.30
	1.52	
	0.86	1.40
	1.38	
23	1.77	1.32
	1.38	
	1.24	1.36
25	1.11	1.31
	1.39	1.42
31	1.17	1.41
	1.22	1.36
38	1.56	1.28
	1.39	
	1.47	1.35
43	1.22	1.41
	1.47	1.34
46	1.17	1.34
	0.91	1.56
51	1.01	1.48
	1.22	1.62
59	1.31	1.39
	1.37	1.40
68	1.22	1.42
	1.47	1.42
70	0.91	1.46
	1.39	
	1.22	1.32
79	1.01	1.53
	1.06	1.48
88	1.44	1.40
	1.22	1.52
94	1.13	1.49
	1.01	1.46

Table 5 (*continued*)

Column no.	Ratio of spoil return to grout	Density of spoil return (10^3 kg/m^3)
137	1.62	1.39
	1.34	
	1.37	1.42
145	1.52	1.41
	1.43	
	1.06	1.42
156	1.26	1.33
	1.37	1.42
175	1.47	1.39
	1.31	1.43
187	1.17	1.43
	1.17	1.52
Avg.	1.30	1.42
Type 3		
8	1.56	1.37
	1.33	
	1.37	1.40
22	1.67	1.36
	1.34	
	1.11	1.43
28	1.11	1.39
	1.01	1.45
60	0.86	1.39
	1.24	
	1.11	1.56
71	1.26	1.36
	1.26	1.32
73	1.06	1.44
	1.37	1.37
76	1.11	1.38
	1.42	1.42
78	1.22	1.49
	1.11	1.52
85	1.52	1.51
	1.11	1.59
86	1.22	1.52
	1.17	1.44
95	1.06	1.47
	1.37	1.49
102	1.37	1.39
	1.42	1.44
105	1.26	1.47
	1.72	1.41
	1.42	
130	1.06	1.40
	1.52	1.36
138	1.47	1.32
	1.31	1.42
139	1.62	1.45
	1.34	
	1.37	1.46
146	1.37	1.39
	1.31	1.38
147	1.37	1.34
	1.31	1.37
157	1.11	1.42
	1.13	1.36
165	1.72	1.42
	1.39	
	1.22	1.44
Avg.	1.30	1.42

Table 5 (*continued*)

Column no.	Ratio of spoil return to grout	Density of spoil return (10^3 kg/m^3)
Type 4		
14	1.06	1.37
	1.06	1.40
19	1.01	1.49
	1.17	1.49
24	1.22	1.47
	1.06	1.51
29	1.47	1.39
	1.42	1.42
35	1.87	1.28
	1.45	
	1.26	1.45
80	1.11	1.37
	1.22	1.42
87	1.77	1.34
	1.40	
	1.37	1.43
96	1.92	1.50
	1.43	
	1.42	1.56
Avg.	1.35	1.43
Type 5		
164	1.22	1.44
	1.37	1.47
Avg.	1.29	1.46
Type 6		
9	1.37	1.43
	1.37	1.47
Avg.	1.37	1.45
Summary		
Overlapping type	Volume ratio of spoil to grout	Density of spoil return (10^3 kg/m^3)
Type 0	1.24	1.39
Type 1	1.31	1.39
Type 2	1.30	1.42
Type 3	1.30	1.42
Type 4	1.35	1.43
Type 5	1.29	1.46
Type 6	1.37	1.45

mixed with native soil. However, these spoil densities are overestimated because the mean ratio of 1.302 of spoil return volume to grout volume is larger than 1. An adjusted factor defined as the ratio of the sum of column volume and spoil volume (1.302 times of grout volume) to the sum of column volume and grout volume is suggested in this paper to provide a rational estimate of spoil density. The column diameter most likely achieved in the field can be estimated by referring the measured mean spoil density of 1.41×10^3 kg/m^3 (Table 3) to the adjusted spoil density, as summarized in Table 4.

This back-calculated diameter of jet grout column is 1.56 m, slightly smaller than the design diameter of 1.6 m by 2.5%. Overall, the scatter in the column diameters reflects the natural variability of the soil type and the strength within the interlayered soil deposits of silty clay and silty sand. To improve the accuracy of quality control, a larger container, e.g., 1 l, to be filled with spoil and a digital balance for weighing spoil has

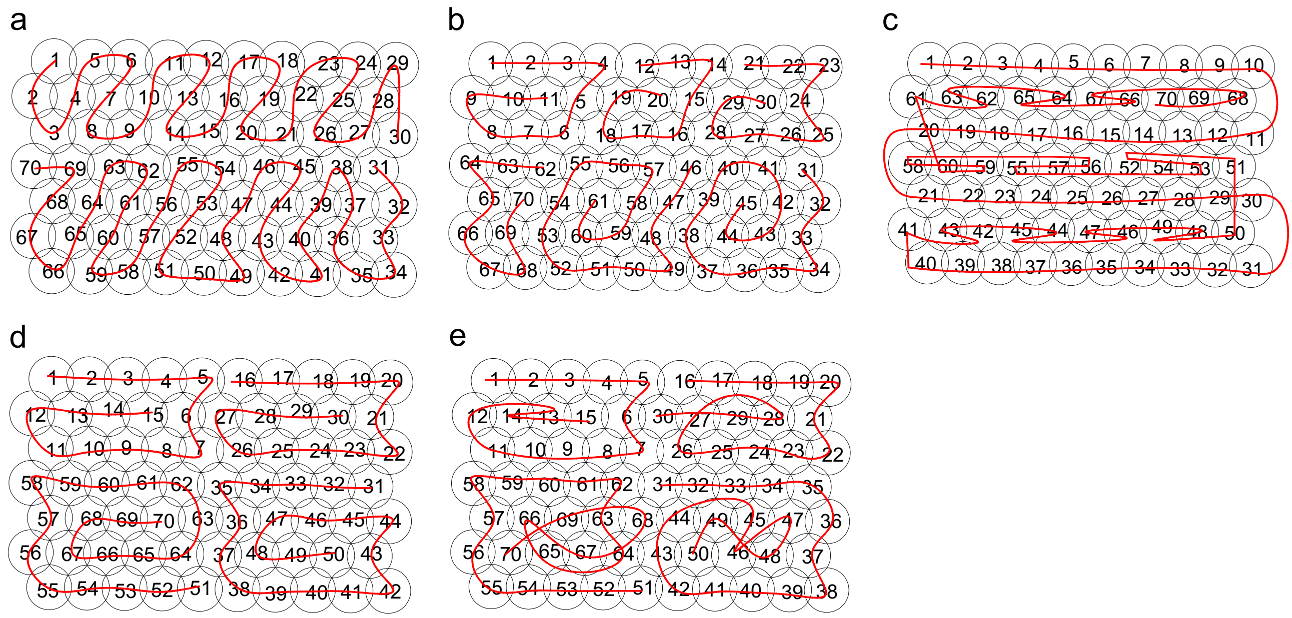

Fig. 8. Types of the grout hole layout.

Table 6
Column overlapping types among various grout hole layouts.

Column overlapping type	0	1	2	3	4	5	6	Total	Type 4+5+6
Layout 1	1	11	21	28	5	4	0	70	9
Layout 2	1	29	11	9	7	7	6	70	20
Layout 3	4	36	3	0	11	5	11	70	27
Layout 4	1	28	12	9	6	10	4	70	20
Layout 5	1	29	13	8	6	4	9	70	19

proved to be very encouraging in measuring the spoil density instead of using mud balance (Langhorst et al., 2007).

8. Grout column installation sequence

To minimize the risk of any leakage of water or soil, a jet grout block must be installed by many overlapping columns with requisite accuracy. Grouting sequence is usually an extremely important parameter which has either a direct or indirect impact on the quality of grouting works (Hurley and Crockford, 2010). In this study, a total of seven types of overlapping columns due to grouting sequence are defined, as shown in Fig. 7. The number of overlapping type indicates that the next column is adjacent to or is circled by the same number of columns. The variations of spoil volume and spoil density for different overlapping types are listed in Table 5. It can be observed that with higher numbers of overlapped columns, larger spoil density was noted, although the small sampling amount for types 5 and 6 may not be sufficiently representative. On the other hand, the correlation between the volume ratio of the spoil return to grout and the overlapping type is not as obvious as to spoil density. Since we already know that the column density is greater than the spoil density, the grouting sequence can be rearranged to have more infill columns (e.g., overlapping type 6) than perimeter columns (e.g., overlapping type 0). As shown in Fig. 8, five grout hole layouts of 70 jet grout columns (10 by 7) with a grouting sequence in red lines are suggested by considering the shortest distance of moving one grouting machine from hole to hole and to provide the most infill columns. Among these layouts, grout hole layout 3 gives the largest number of infill columns of overlapping type 4, 5, and 6 in Table 6 and is apparently the smart choice.

9. Concluding remarks

The tunnel boring machine was successfully driven through the pile foundation below an underground parking building, with not experience of heave or settlement indicated by the monitoring results from electronic beam sensors. From the results and calculations discussed in this paper, the following conclusions can be drawn:

(1) The control chart of the ratio between spoil return volume and grout volume can effectively provide an early warning of sand boiling or groundwater inflow if abnormal frequent violations of the upper control limit is imminent.
(2) A back calculation from the mean values of the spoil density and spoil flow rate provides the estimated column diameter in the field at around 1.56 m, only 2.5% smaller than the design diameter of 1.6 m.
(3) To improve the measuring accuracy of spoil density, a larger volume (e.g., 1 l) container and a digital balance are highly recommended rather than a hydrometer and mud balance.
(4) To optimize the quality of the jet grout column, the grouting sequence can be arranged in a way that more infill columns are jet-grouted. The extra time and effort required to move the grouting machine around also should be taken into consideration.

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The authors wish to acknowledge the contribution of Mr. Pu-Yen Chen who has systematically marshaled massive field records. Thanks are also due to anonymous reviewers for the valuable comments and corrections to improve this manuscript. This research would not have been possible without the financial support from the National Science Council, Taiwan, under Contract no. NSC96-2622-E-027-019-CC3.

References

Croce, P., Flora, A., 1998. Jet-grouting effects on pyroclastic soils. Riv. Ital. Geot. 2, 5–14.

Croce, P., Flora, A., 2000. Analysis of single-fluid jet grouting. Geotechnique 50 (6), 739–748.

Croce, P., Modoni, G., 2007. Design of jet-grouting cut-offs. Ground Improv. 11 (1), 11–19.

Flora, A., Lignola, G., Manfredi, G., 2007. A semi-probabilistic approach to the design of jet grouted umbrellas in tunneling. Ground Improv. 11 (4), 207–217.

Flora, A., Lirer, S.,Monda, M., 2012. Probability design of massive jet grouted water sealing barriers. In: Fourth International Conference on Grouting and Deep Mixing, New Orleans, LA.

Hurley, T.M., 2005. Soil Stabilization Through Jet Grouting. North American No-Dig, Orlando, FL, 2005.

Hurley, T.M., Crockford, R., 2010. Innovative use of jet grouting for earth retention, underpinning and water control. In: 2010 Earth Retention Conference, GSP 208, R. Finno, Y.M.A. Hashash,P. Arduino, (Eds.), American Society of Civil Engineers, Reston, VA., 417-428.

Ho, C.E., 2011. Evaluation of jet grout formation in soft clay for tunnel excavation. In: Han, J., Alzamora, D.A. (Eds.), Geo-Frontiers 2011: Advances in Geotechnical Engineering, GSP 211. American Society of Civil Engineers, Reston, VA (CD-ROM).

JJGA, 2002. Jet Grout Technical Information, 10th ed. Japanese Jet Grout Association (JJGA).

Juran, J.M., 2010. Juran's Quality Handbook, sixth ed. McGraw-Hill.

Kauschinger, L.J., Hankour, R., Perry, E.B., 1992. Methods to estimate composition of jet grout bodies. In: Proceedings of the Conference on Grouting, Soil Improvement and Geosynthetics, GSP 30, R.H. Borden, R. O. Holtz, I. Juran, (Eds.), American Society of Civil Engineers, Reston, VA., 194-205.

Langhorst, O.S., Schat, B.J., de Wit, J.C.W.M., Bogaards, P.J., Essler, R.D., Maertens, J., Obladen, B.K.J., Bosma, C.F., Sleuwaegen, J.J., Dekker, H., 2007. Design and validation of jet grouting for the Amsterdam Central Station. In: XIV European Conference on Soil Mechanics and Geotechnical Engineering, Madrid, Spain.

Lignola, G.P., Flora, A., Manfredi, G., 2008. Simple method for the design of jet grouted umbrellas in tunnelling. J. Geotech. Geoenviron 134 (12), 1778–1790.

Malinin, A., Gladkov, I., Malinin, D., 2010. Experimental research of jet-grouting parameters in different soil conditions. In: Proceedings of sessions of GeoShanghai 2010 International Conference, GSP 206, F. Tonon, X. Liu, W. Wu, (Eds.), American Society of Civil Engineers, Reston, VA, 49-54.

Miki, G., Nakanishi, W., 1984. Technical progress of the jet grouting method and its newest type. In: Proceedings of the International Conference on In Situ Soil and Rock Reinforcement, Paris, pp. 195–200.

Modoni, G., Croce, P., Mongiovì, L., 2006. Theoretical modeling of jet grouting. Geotechnique 56 (5), 335–347.

Ni, James C., Cheng, W.C., 2012. Characterising the failure pattern of a station box of Taipei Rapid Transit System (TRTS) and its rehabilitation. Tunnelling Underground Space Technol. 32, 260–272.

Stark, T.D., Axtell, P.J., Lewis, J.R., Dillon, J.C., Empson, W.B., Topi, J.E., Walberg, F.C., 2009. Soil inclusions in jet grout columns. DFI J. 3 (1), 33–44.

Wang, S.Y., Chan, D.H., Lam, K.C., Au, S.K.A., 2013. A new laboratory apparatus for studying dynamic compaction grouting into granular soils. Soils Found. 53 (3), 462–468.

Western Electric Company, 1956. Statistical Quality Control handbook, first ed. Western Electric Co., Indianapolis, IN.

Xu, H.Y., Chen, L.Z., Deng, J.L., 2014. Uplift tests of jet mixing anchor pile. Soils Found. 54 (2), 168–175.

Yahiro, T., Yoshida, H., Nishi, K., 1982. Soil improvement method utilizing a high speed and air jet (column jet grout method). In Sixth International Symposium on Jet Cutting Technology, Surrey, British Columbia.