

Performance of Rapid-Jet system for soil improvement works in soft marine clay

Takeshi Iwakubo¹, R.K.N. Wong¹, G.K. Leong², Y.F. Weng³, J. Chu⁴ and S.-H. Cheng⁵

¹ SANSBIN Corporation Ltd., Taipei, Taiwan.

² Global Civil Engineering Pte. Ltd, Singapore.

³ China Railway First Group Co., Ltd., Singapore.

⁴ Nanyang Technological University, Singapore.

⁵ National Taiwan University of Science and Technology, Taipei, Taiwan.

ABSTRACT

This paper reports a case study of using the Rapid-Jet system for installation of jet grout piles (JGP) in soft marine clay of up to 44.8 m. The use of JGP is part of the ground improvement works for the construction for one of the tunnelling project that are constructed by China Railway First Group Co. Ltd. Singapore Branch in Singapore. The tunnel went through a soft marine clay layer which needed to be grouted from below the tunnel to the Old Alluvium (OA) layer. At the project site, there was a 1.8 m outer diameter storm water pipe crossing the tunnel alignment at 8m below ground level. The pipe obstructed the installation of JGP piles in marine clay. The Rapid-Jet method was adopted. The nominal diameter of the JGPs was 3.0 m which was verified by the sound detector during jet grouting and excavation after installation. 24 samples were taken for unconfined compression tests. The total coring recovery (TCR) for each core were also recorded. Based on the JGP trial panel testing results, the working parameters were proven to be suitable for the formation of 1.5, 2.0, 2.5 and 3.0 m diameter grouting column for the JGP works. The TBM tunnelling works were completed successfully without causing ground settlement exceeding the limit.

Keywords: case study, jet grouting, marine clay, soil improvement

1 INTRODUCTION

For the construction of the tunnelling project in Singapore undertaken by China Railway First Group Co. Ltd. Singapore Branch, a tunnel was to be constructed through a layer of soft marine clay. The marine clay from below the tunnel until the top of the Old Alluvium layer needed to be improved. Deep Soil Mixing (DSM) would be normally adopted for similar cases. However, there was a 1.8 m outer diameter storm water pipe crossing the tunnel alignment at 8 m below the ground level. The pipe was supported by RC piles below. With the existence of this pipe, the DSM method could not be adopted and the Rapid-Jet system for installation of large diameter of JGP was used instead. The large diameter JGPs served 2 purposes: 1) to improve the soft marine clay and 2) to grout to the bottom of the storm water pipe as a support to transfer the load below as the piles had to be cut away during TBM boring. The average grout depth was 37 m and the average drill depth was 45 m.

2 SITE CONDITIONS

The site and trial panel location is shown in Figure 1. The soil profile along Section F is shown in Figure 2. The existing ground level was at 105.5 mRL. The 1.8 m outer diameter storm water pipe is shown in Figure 2. At 8 m below the ground level, the storm water pipe

was used to channel excessive rainwater from the golf course crossing the site to the Reservoir. The cross-sections of the two tunnels passing through soft marine clay is also shown in Figure 2. The groundwater level was about 1.8 m below the ground level. The soil profile can be divided into five layers: (1) the sand fill layer with an average depth of 14.5 m consisting of fine to coarse grained sand with gravels. The SPT N value ranged from 3 to 16 in this layer; (2) the very soft upper marine clay layer (Kallang Formation) with a depth to 23 m; (3) the stiff fluvial clay layer (Kallang Formation, F2) with a depth to 28.7 m and SPT N value of 8 ~ 9; (4) the very soft lower marine clay layer (Kallang Formation) with a depth to 44.8 m; and (5) the Old Alluvium (OA) layer consisting of medium-dense to dense cemented clayey sand with a depth to 44.8 m and SPT N value of 24 ~ 36.

3 RAPID-JET TECHNOLOGY

Similar to the commonly used JSJ method, the large diameter jet grouting method (commercially named the Rapid-Jet method) uses a double-tube grouting system with two nozzles on the opposite side of the monitor. The latter also uses air and jet stream to cut and mix the in-situ soil with grout. A larger nozzle diameter of 3~4.2 mm is used to allow for a larger grouting rate. The jet grouting parameters of this

method are similar to those proposed by Burke (2004) and Lunardi (1997). The grouting parameters used here are as follows: grouting pressure = 30~34 MPa, grouting rate = 120 ~ 380 L/min, and rod rotation and withdrawal rate = 3~10 rpm and 10~12 min/m. Using these parameters. So, it can rapidly install a grout pile with a diameter up to 2.0~3.5 m at a depth up to 50 m below ground surface. There are two categories in Rapid-Jet system – R1 and R2, in which particular parameters are available as shown Table 1. Each category involves representative equipment. Rapid-Jet monitor water test and typical installation procedure as shown in Figure 3 and 4. Acoustic monitoring device is shown in Figure 5, it can be used to detect the quantitative intensity of erosion by jet grout and helps to assess the column diameter (Cheng et al. 2017). This system collects eroding sound at monitoring pipes located on several positions as shows in Figure 5. Sound collectors are synchronized with jet grout depth.

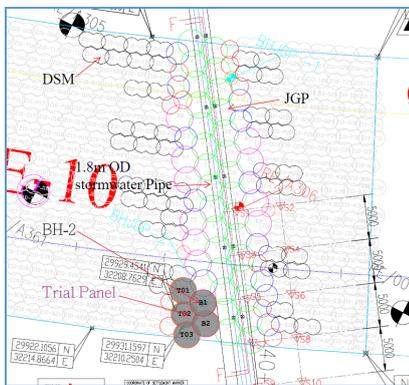


Fig. 1. Site and trial panel location

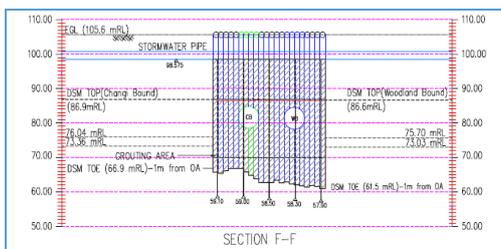


Fig. 2. Cross section F-F



Fig. 3. Water jet of Rapid-Jet (Type R2)

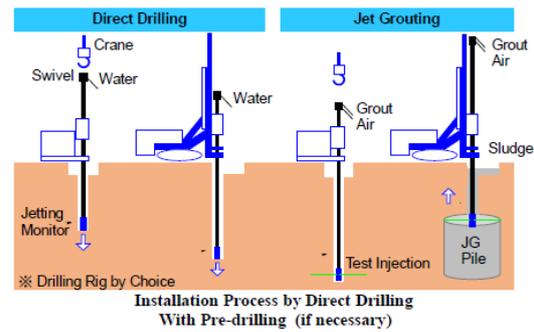


Fig. 4. Typical Rapid-Jet Installation Procedure

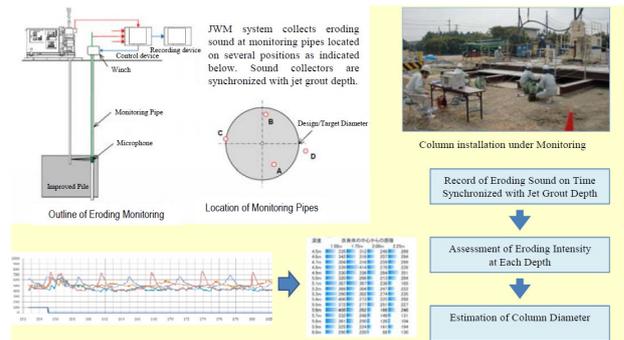


Fig. 5. Rapid-Jet Jet Acoustic Monitoring System

Table 1. Rapid-Jet Standard Construction Specifications

| Type | R1 | R2 |
|------------------------------------|-----------------|-----------------|
| Column Diameter,m | 2 ~3 | 3~3.5 |
| Drilling method | Direct drilling | Direct drilling |
| Installation method | Double tube | Double tube |
| Grout Pressure,MPa | 30~34 | 30~34 |
| Grout Flow Rate ,L/min | 120 ~ 260 | 300 ~ 380 |
| Air Pressure ,MPa | 0.70 ~ 1.1 | 0.70 ~ 1.1 |
| Air Flow Rate ,m ³ /min | Over 6 | Over 10 |
| 1 Step ,cm | 2.5 | 2.5 |
| Lift Rate,min/m | 10 ~ 12 | 10 ~ 12 |

4 TRIAL TEST

Five JGP trial panels T01, T02, T03, B1 and B2 with sound pipes were carried out. Each panel consisted of a 3 m diameter JGP column to a depth of about 46.6 m. 4 coring Points a, b, c, d were used to obtain cores through the full depth of the grouted block as shown in Figure 6. The JGP installation summary is given in Table 2.

In order to verify the pile diameter constructed by the Rapid-Jet method under various grouting parameters and in different soil conditions, Pile T01 was selected to test the grouting diameter using the Jet Wave Monitoring System (JWM). Prior to the JGP works, 3 pipes were installed vertically from the ground level to 3 m into the OA layer by drilling method. Positions of these 3 points were 1.25, 1.5 and 1.75 m from the center of T01 respectively. The layout of sound detector points is shown in Figure 7. A surface test at depth 0.5 m with thickness of about 1 m was done. After excavation, a pipe head with a diameter of about 3.5 m was exposed as shown in Figure 8. The jet

wave monitoring results and Jet grout parameters obtained are shown in Figure 9. It can be seen from Figure 9 that the grout pile has a minimum diameter of 3.0 m.

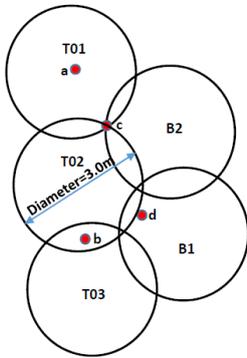


Fig. 6. JGP trial panel

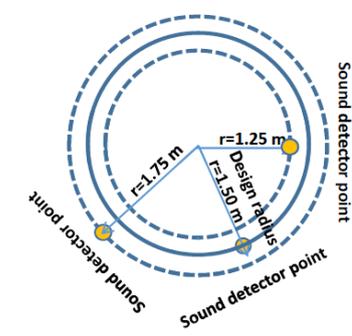


Fig. 7. Layout of sound detector points

Table 2. Rapid-Jet Standard Construction Apparatus

| No. | Date of Grout | Pile No | Grout Top Level (mRL) | Grout Toe Level (mRL) | Grout Volume (m ³) (Dia=3m) |
|-----|---------------|---------|-----------------------|-----------------------|---|
| 1 | 2-Jan-18 | T1 | 98.58 | 58.95 | 280.13 |
| 2 | 5-Jan-18 | T2 | 98.58 | 58.93 | 280.27 |
| 3 | 9-Jan-18 | T3 | 98.58 | 58.96 | 280.06 |
| 4 | 10-Jan-18 | B1 | 98.58 | 58.86 | 280.76 |
| 5 | 13-Jan-18 | B2 | 98.58 | 58.94 | 280.20 |

Note: Existing Ground Level=105.5 m



Fig. 8. Exposed Jet Grouting column of T01 with a diameter of 3.5 m.

| Actual T-01 | Length | Test Pipe Location | | | Jet Grouting Parameter | Depth |
|--------------|--------|--------------------|----------------|----------------|---|--------|
| | | ±0.2m (+1.25m) | ±0.2m (+1.50m) | ±0.2m (+1.75m) | | |
| Fill Sand | 98.72m | | | | | 98.72m |
| Marine Clay | 98.17m | ○ | ○ | △ | Jet Grouting 32Mpa, 300L/min, 10min/m, 5gpm | 98.20m |
| | 98.20m | ○ | ○ | △ | Jet Grouting 32Mpa, 300L/min, 12min/m, 5gpm | 98.24m |
| | 98.24m | ○ | ○ | △ | Water Pre Cutting 25Mpa, 340L/min, 10min/m, 5gpm | 98.28m |
| F2 Soft Clay | 98.28m | ○ | ○ | △ | Jet Grouting 32Mpa, 340L/min, 12min/m, 5gpm | 98.30m |
| | 98.30m | ○ | ○ | △ | Test Pipe Trouble | 98.38m |
| Marine Clay | 98.38m | ○ | ○ | △ | Jet Grouting 32Mpa, 340L/min, 10min/m, 5gpm | 98.42m |
| | 98.42m | ○ | ○ | △ | Water Pre Cutting 25Mpa, 340L/min, 10min/m, 5gpm | 98.42m |
| | 98.42m | ○ | ○ | △ | Jet Grouting 32Mpa, 340L/min, 12min/m, 5gpm | 98.48m |
| OA | 98.48m | ○ | ○ | △ | Jet Grouting 32Mpa, 340L/min, 12min/m, 5gpm | 98.48m |

Fig. 9. Acoustic Monitoring System results and Jet grout parameter

5 JGP CORING TEST RESULTS

The treated soils shall obtain a minimum compressive strength of 1.6 MPa, and a minimum stiffness of 280 MPa as evaluated in accordance with BS1377 (1990: Part 7). The minimum Total Coring Recovery (TCR) required is 85%. Variations in Unconfined Compressive Strength (UCS), Modulus of Elasticity (E₅₀), and TCR with depth as shown in Figure 10. Summary of JGP test results based on coring points and soil stratum as shown in Tables 3 and 4.

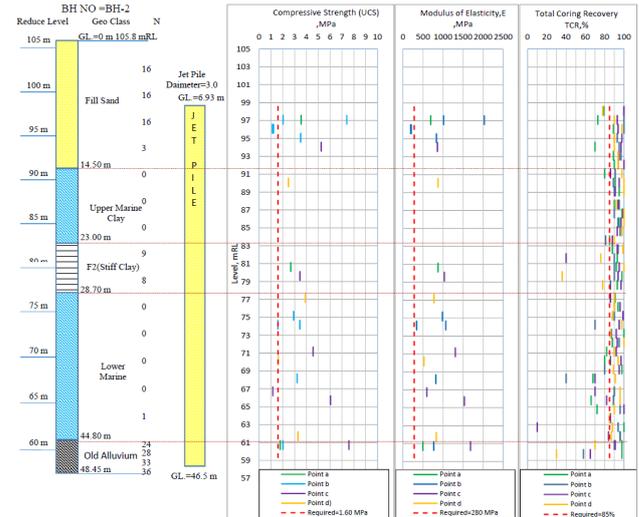


Fig. 10. Variations in UCS, E50 and TCR with depth and approximate soil profile. 5.1 Unconfined Compressive Strength

Table 3. Summary of JGP Test Results Base on Coring Point

| Coring Point No | Date of Test | UCS, kPa | | | Elasticity (E ₅₀), MPa | | | TCR, % | | |
|-----------------|--------------|----------|------|------|------------------------------------|-----|------|--------|-----|-----|
| | | Avg | Min | Max | Avg | Min | Max | Avg | Min | Max |
| a | 13/2/2018 | 2700 | 1786 | 3555 | 660 | 499 | 874 | 89 | 66 | 100 |
| b | 12/2/2018 | 2847 | 1125 | 7404 | 827 | 190 | 2034 | 89 | 40 | 100 |
| c | 12/2/2018 | 4670 | 1153 | 7584 | 1169 | 595 | 1685 | 88 | 10 | 100 |
| d | 13/2/2018 | 2820 | 1622 | 3890 | 752 | 523 | 875 | 88 | 30 | 100 |

Table 4. Summary of JSP Test Results based on soil Stratum

| Soil Layer | Level m RL | SPT N | UCS, MPa Require=1.6 MPa | | | Elasticity (E ₅₀), MPa Require=280 MPa | | | TCR, % Require=85% | | |
|-------------------|--------------|---------|-----------------------------|------|------|---|-----|------|-----------------------|-----|-----|
| | | | Avg | Min | Max | Avg | Min | Max | Avg | Min | Max |
| Fill Sand | 105.8 ~ 91.1 | 3 ~ 16 | 3.33 | 1.13 | 7.40 | 817 | 190 | 2034 | 91 | 70 | 100 |
| Upper Marine Clay | 91.1 ~ 82.4 | 0 | 2.48 | -- | -- | 875 | -- | -- | 94 | 81 | 100 |
| Fluvial Clay (F2) | 82.4 ~ 75.8 | 8 ~ 9 | 3.63 | 3.45 | 3.89 | 833 | 692 | 1032 | 86 | 36 | 100 |
| Lower Marine Clay | 75.8 ~ 60.8 | 0 ~ 1 | 2.96 | 1.15 | 6.04 | 851 | 339 | 1532 | 87 | 10 | 100 |
| Old Alluvium (OA) | 60.8 ~ 58.8 | 24 ~ 36 | 4.09 | 2.02 | 7.58 | 1108 | 766 | 1685 | 63 | 30 | 98 |

The average of UCS for points a, b, c, d are 2.70, 2.85, 4.67 and 2.82 MPa, respectively, and is ranging from 2.48 to 4.09 MPa for all soil layers. The minimum UCS is 1.13 MPa which is less than the required 1.6 MPa. The maximum UCS is 7.58 MPa. We noted that the strength verification for point a & d complied with the requirement for all levels. There are 2 samples from point b (at 96.575 - 95.575 mRL & 74.675 - 73.675 mRL) and 1 sample from point c (at 67.225 - 66.225 mRL) did not meet the strength requirement. Subsequently additional 2 samples were selected above and below the failed samples (6 in total) and sent for testing. Unfortunately one of the sample (Point b at 96.575 - 95.575 mRL) still did not meet the strength requirement. By examining the samples tested, a pocket

of voids in due to the existence of foreign material was found. In order to clear the doubts, GCE conducted additional corings beside Point b (98.575 - 95.575 mRL) and 2 additional samples were selected for testing. These samples complied with the strength requirement. More coring and testing were taken during the actual grouting works and the strength requirements were met.

5.2 Modulus of Elasticity (E_{50})

The average E_{50} for points a, b, c, d are 660, 827, 1169 and 752 MPa and is ranging from 817 to 1108 MPa for all soil layers. The minimum E_{50} is 190 MPa which is less the requirement of 280 MPa and the Maximum E_{50} is 2034 MPa. We noted that the E_{50} verification for point a, c & d complied with the requirement at all levels. There is 1 sample from point b (at 96.575 - 95.575 mRL) E_{50} is 190 MPa. Subsequently one additional sample was selected and sent for testing and the measured stiffness is 207 MPa which failed to meet the strength requirement too.

5.3 Total Core Recovery

The average value of TCR for points a, b, c and d are 89, 89, 88 and 88% respectively. The average TRC ranges from 63% for the OA layer to 94% for the Upper Marine Clay layer, and the minimum value for Fill Sand, Upper marine Clay, F2, Lower Marine Clay and OA are 70, 81, 36, 10 and 30% respectively. There are several reasons for causing the TCR to be less than 85% which include:

- Core loss due to washing out by the water used for drilling;
- Presence of sand lenses which might crumble when grouted and lost after coring;
- Slight rotation/inclination of the rods due to stiffer points could cause core loss

A more important requirement is to determine whether the core is grouted or is largely native soil. If the core removed shows ungrouted material, this could be due to many issues including the formation of smaller diameter column. If a core loss is generally sporadic but overall cemented and the average TRC is larger than 85%, The grouting should be considered as satisfying the TRC requirement.

6 ACTUAL JGP AND TUNNEL CONSTRUCTION

Actual JGP works started in April 2018 and was completed in June 2018. In total, 72 numbers of JGP columns were installed and the JGP parameters are shown in Table 5. There were settlement markers installed in various locations. The settlements monitored during the course of JGP were consistent and did not breach the pre-determined level.

CRFG 1st TBM reached below the storm water pipe in August 2018. They have carried out the Cutter Head Inspection (CHI) in the JGP grout block. There was only a minor leak spot with 0.5 l/min ingress of water. They

completed the CHI including cutting away the RC piles within 3 days and proceeded with the tunnelling work. The 2nd TBM reached 3 weeks later. Their TBM cut through the RC Piles easily. They did not carry out the CHI as planned as they believed it was not necessary. Both TBM already reached the receiving shaft and the tunnelling works have completed in October 2018.

Table 5. JGP Parameter for Actual JGP works

| Description | JGP Parameter | | | |
|----------------|---------------|---------|---------|---------|
| | 1.5m | 2.0m | 2.5m | 3.0m |
| Diameter | 1.5m | 2.0m | 2.5m | 3.0m |
| Pile Nos | 3 | 11 | 12 | 46 |
| Blind Bore | | | | |
| Speed (min/m) | 1.0~1.5 | 1.0~1.5 | 1.0~1.5 | 1.0~1.5 |
| Water Precut | | | | |
| Speed (m/min) | 5~6 | 5~6 | 5~6 | 5~6 |
| RPM | 3~10 | 3~10 | 3~10 | 3~10 |
| Pressure (Bar) | 300 | 300 | 300 | 300 |
| Jet Grout | | | | |
| Speed (m/min) | 10~12 | 10~12 | 10~12 | 10~12 |
| RPM | 3~10 | 3~10 | 3~10 | 3~10 |
| Pressure (Bar) | 300 | 300 | 350 | 350 |
| Flow (l/min) | 140~180 | 160~200 | 200~300 | 300~380 |
| Grout Ratio | 1:1.2 | 1:1.2 | 1:1.2 | 1:1.2 |
| Withdrawal | | | | |
| Speed (m/min) | 2~3 | 2~3 | 2~3 | 2~3 |

7 CONCLUSION

Based on the JGP trial panel testing results, the working parameters were proven to be suitable for the formation of 1.5, 2.0, 2.5 and 3.0 m diameter grouting column for the JGP works to enhance the ground stability for the soil below the existing storm water pipeline in the project. The TBM tunnelling works were completed successfully without causing ground settlement exceeding the limit.

ACKNOWLEDGEMENTS

The Authors are indebted to the following organizations: Global Civil Engineering Pte. Ltd Singapore and SANSHIN Corporation (Taipei Branch) for carrying out the field work of the Rapid-Jet JGP grouting and the main contractor China Railway First Group Co., Ltd. Singapore Branch for providing valuable construction records for the writing of this paper.

REFERENCES

- BSI (2001) BS EN 12716: Execution of special geotechnical work – Jet grouting, BSI, London, UK.
- Burke, G.K. 2004. Jet grouting systems: Advantages and disadvantages. In Proceedings of Drilled shafts, Micropiling, Deep mixing, Remedial method, and Specialty foundation systems, Orlando, Florida, 29-31 January 2004. American Society of Civil Engineers, New York, pp. 218-234.
- Cheng, S.H., Liao, H.J., Yamazaki, J., and Wong, R.K.N. 2017. Evaluation of jet grout column diameters by acoustic monitoring. Canadian Geotechnical Journal, 54 (12), 1781-1789. doi.org/10.1139/cgj-2017-0025.
- Lunardi, P. 1997. Ground improvement by mean of jet grouting. Proceedings of Institution of Civil Engineers—Ground Improvement, 1 (2), 65-85. doi: 10.1680/gi.1997.010201.