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Performance of V-JET method for arrival of shield tunnelling machine

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ABSTRACT: This paper reports a case study of jet grouting project which involves constructing a watertight grouted zone under a drainage culvert as part of the arrival process for shield machine. To minimize the number of grouting hole drilling in a congested street, the V-JET method which consisted of a modified jet nozzle and an increased flow rate and jet grouting pressure was adopted for this project. Among the 38 grouting holes of 20 m deep drilled in this project, 10 were drilled through the culvert. All grout piles are expected to have a nominal diameter of 3.5 m, which was verified later with sound detectors during jet grouting. The strength of grouted piles indicated can meet the design specifications (2.36 MPa for silty clay and 3.25 MPa for silty sand). The entire jet grouting project of 1750 m^3 in cement grout volume (W/C = 1.22) was finished in 105 days. It can assure the stabilization and waterproof of soil around cutting face of arrival shield tunneling. The work of joint shield tunnel and the existing station was successfully accomplished.

1. INTRODUCTION

Causes of traffic congestion, difficulties of obtaining construction sites, and other environmental factors result in an intense demand for grate utilization of underground spaces in urban areas. Taking Taipei MRT for example, more than 2/3 of construction was built underground over the past two decades. However, under the rapid development of urbanization, there might be conflicts between the progressing construction projects and their nearby infrastructure’s foundation, drainage culvert, utility networks or other underground facilities, which increase construction difficulties and risks.

In the last decade, increasing demand for underground space in urban areas has been goes for shield tunneling technological progress, especially ground improvement measures such as grouting or artificial ground freezing. It provides pre-supporting of soil in order to increase safety of construction project, has been limit the need of costly and time-consuming (Anagnostou and Rizos, 2009). Hence, in the construction experience of Taipei MRT, jet grouting method is widely applied for stabilization and waterproof of soil around shield tunneling machine and underground stations. It also lowers risks of negative effect on third parties. But in recent years, as mentioned earlier, the limitation and complexity of underground space of other uses involve multiple constraints and potential conflicts. This increases more challenge to the design and construction of jet grouting method in the ground improvement work.

This paper will report a case study of jet grouting project, which involves the construction of a water tight grouted zone under a drainage culvert, for the arrival of shield machine of Tucheng extension line (Yongning Station → Dingpu Station) in Taipei MRT. To minimize the number of grouting holes drilling in a congested street, the V-JET method was adopted. This study will present the histories of jet grouting carried out in the field and the measures taken to ensure the quality of jet grout piles.

2. SITE CONDITIONS

Tucheng extension line (Yongning Station → Dingpu Station) of Taipei MRT is located in the southern part of Taipei Basin. The depth of shield tunnel ranges from 9.58 m to19.82 m below ground surface. Its subsoil condition varies from silty clay, silty sand to weathering sandstone. Along the Tucheng extension line, four sites are considered to have high risk potential, namely the departure site of shield machine (at Dingpu station), the arrival site (at Yongning station) and two cross-passage sites between shield tunnels (Figure 1). Double packer (DP) grouting method and jet grouting method are used to improve the mechanical properties and water tightness of soil near the high risk sites. To better understand the subsoil properties of the sites, a thorough geological investigation was carried out at each ground improvement site. The SPT-N values, grain size distribution and physical soil properties profiles are shown in Figure 2. The subsoil condition near Yongning Station (arrivel site of shield tunnel), the groundwater level at site is 3.7 m below surface, The upper 12.5 m of silty clay layer has some drifted wood embedded. It has the undrained shear strength (S_u) about equal to 30 KPa. Between the depth of 12.5m to 22 m, it is a silty sand layer (friction angle $\phi' = 28^o \sim 30^o$) embedded with large numbers of drifted wood. Below the depth of 22 m, it is mostly loosely cemented weathering sandstone and with the unconfined compressive strength (q_u) equal to 5~20 MPa.

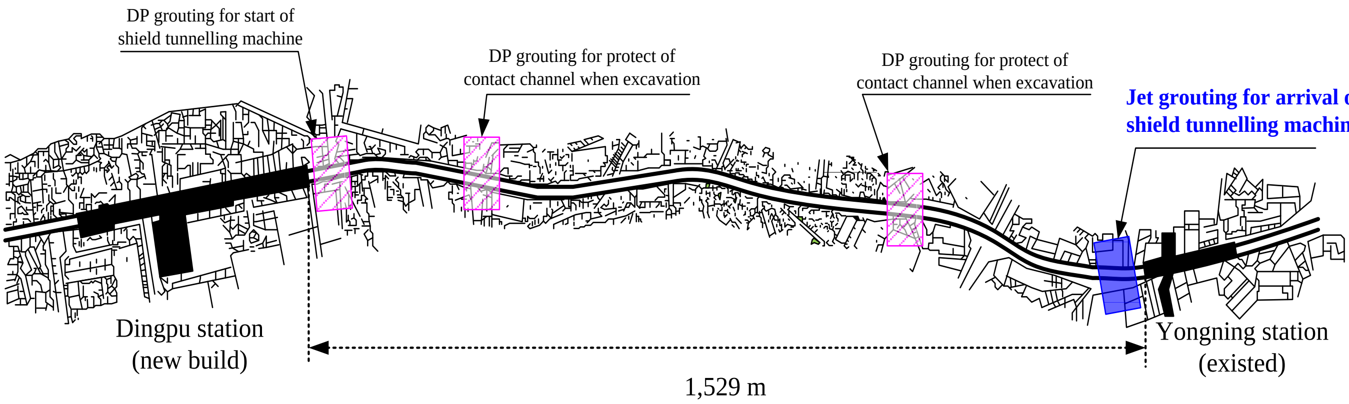


Figure 1. The route and improvement zones of pre-construction condition of Tucheng extension line, Taipei MRT

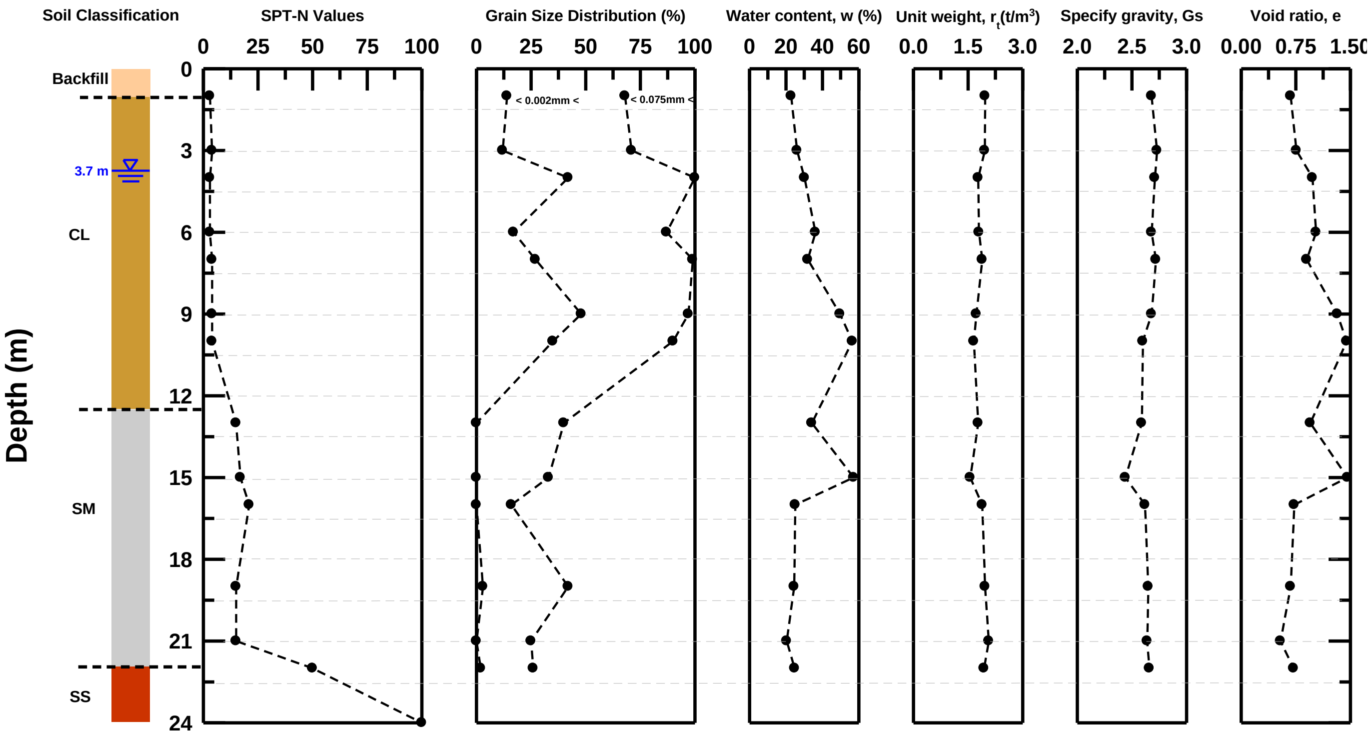


Figure 2. The SPT-N values, grain size distribution and soil properties profiles of arrival site (at Yongning Station)

3. DESIGN AND GROUTING METHODS

The zone to be grouted for the arrival of shield tunneling machine is equal to 2,426 m^3 [approximate dimension of 24m (L) X 10m (W) X 10m (H)]. The arrival site is located under a busy main street of Tucheng city and is near the residential area, too. The traffic and noise problems are two main concerns for this jet grouting project. In addition, the zone to be grouted was in conflict with the nearby utility network and the drainage culvert (Figure 3). Due to the complexity of the project, it is necessary to have a detailed study on the construction methods in advance before carrying out the grouting job to minimize the risk involved. Evaluation on the design and grouting methods taken before construction are illustrated as follows:

3.1 Design evaluation

Since there is a drainage culvert located between ground surface and shield tunnels, trial layouts of drilling holes was adopted before jet grouting. Both the inclined holes and vertical holes layouts were used to study the optimum drilling plan and grout pile diameter for this jet grouting job. As shown in Figure 4(a), if the grout pile with the diameter equal to 1.2 m is adopted and the drainage culvert needs to be avoided, totally 345 grout holes in total. It includes 161 inclined grout holes with dip angles varying from 18^o to 36^o. Alternatively, Figure 4(b) shows the grout holes layout without inclined holes. But it needs to drill 92 grout holes through the drainage culvert. It is concerned that drilling so many holes through the drainage culvert may have a bad effect on the integrity and function of the culvert. Especially, it may result in a serious leaking problem for the drainage culvert. So, the grout holes layouts shown in Figures 4(a) and 4(b) was not adopted. Instead, the grout holes layout of Figure 4(c) was used to reduce the numbers of grout holes to 38 and only 10 holes must be drilled through the culvert. It certainly can maintain a better function of the drainage culvert and consequently minimize the risk involved in the jet grout practice. To carry out the grouting job of Figure 4(c), the designed diameter of grout pile must be more than 3.5 m. So the jet nozzle of the monitor and the grouting parameters such as flow rate, grouting pressure, and rod withdraw rate and rotation rate are needed to be modified accordingly.

3.2 Outlines of V-JET method

Similar to the commonly used JSG method, the V-JET method uses a double-tube grouting system with two nozzles on the opposite side of the monitor in different levels. 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 a larger grouting rate. The grouting parameters used here are as follows: grouting pressure = 33~37 MPa, grouting rate = 180 or 360 or 540 *l*/min, and rod rotation and withdrawal rate = 2~5 rpm and 10~18 min/m. Using these parameters, the grouting capacity can be increased to 35.3 m^3/hr. So, it can rapidly install a grout pile with a diameter up to 2.0~5.5 m at a depth up to 50 m below ground surface. More details of the V-JET method and comparison with existing grout methods are illustrated in Table 1.

4. PERFORMANCE OF GROUTING WORK

During construction, in order to proceed ground improvement, it is required to prevent the nearby soils from collapsing or water and sand gushing while the closed shield machine was arriving Yonging Station to pass through diaphragm wall in order. Within limited space and under the condition of obstacle of drainage culvert and utility networks, V-JET method is applied in construction according to design evaluation. After improvement, the compressive strength of silty clay layer is set to increase to 1.2 MPa, while that of the silty sand layer is set to increase to 2.0 MPa and the permeability of the improved zone is set to less than 1×10^{-5} cm/sec.

To avoid causing traffic problems on busy roads, this grouting project was carried out in three different stages: (1) Find out the underground obstacles and remove them. Carry out the pilot grouting test. Complete 14 grout piles on the southern side of the drainage culvert. (2) Drill 10 grout holes through the culvert. Seale the annular space between drill rod and bored hole on the upper and lower slab with water seal box. Construct the grout piles beneath the drainage culvert. (3) Complete 14 grout piles on the northern side of the drainage culvert. The details of the jet grouting work are shown in Table 2 and Figure 5.As shown in Table 1, the numbers of nozzle adopted for the V-JET grouting were 2 and the flow rate was 360 *l*/min compared to 1 nozzle and 60 *l*/min flow rate used for traditional JSG method. Meanwhile, the rod rotation rate was decreased to 2-5 rpm to allow the grout jet to cut deeper into the soil. But the overall grouting time was not slow down because the rod withdraw rate was increased to 12 min/m to compensate the slower rotation rate. Totally, 38 jet grout piles (diameter = 3.5 m, grouted depth varied from 9.58 to 19.82 m below grout surface) were installed at the arrival site of shield machine. Grout material used in this jet grouting project was slag cement with the water-cement ratio equal to 1.22. Table 1 summarizes the grouting parameters adopted in this project and the comparison with existing grout methods.

(a) Busy traffic above improvement zone (b) Drainage culvert above improvement zone (c) Utility networks above improvement zone

Figure 3. Pre-construction condition of arrival site of shield machine (nearby Yongning Station)

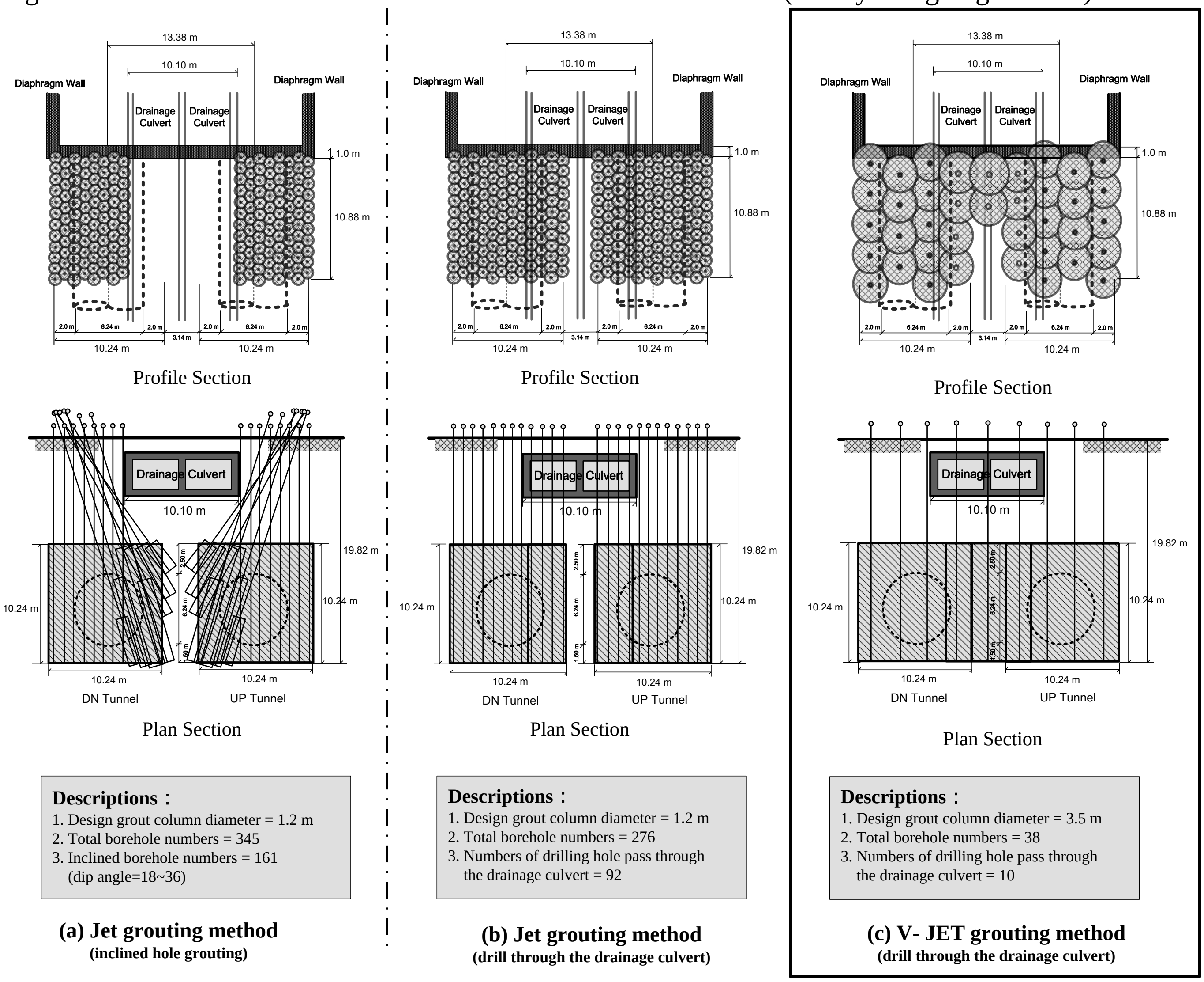


Figure 4. Proposed jet grouting layouts for the arrival site

Table 1. Comparison of different jet grouting methods (after Yong et al., 1996; Yoshida et al., 1996)

Item \ Method		Jet Special Grout (JSG method)	Column Jet Grout (CJG method)	Rodin Jet Pile (RJP method)	V-JET method
Effective diameter		ϕ 1.0 ~ 2.0 m	ϕ 1.2 ~ 2.0 m	ϕ 2.0 ~ 3.0 m	ϕ 2.5 ~ 4.5 m
Geological condition	Sand	SPT-N ≤ 50	SPT-N ≤ 200	SPT-N ≤ 100	SPT-N ≤ 100
	clay	SPT-N ≤ 4	SPT-N ≤ 9	SPT-N ≤ 5	SPT-N ≤ 5
Design strength	Sand	2 ~ 3 MPa	2 ~ 3 MPa	2 ~ 3 MPa	2 ~ 3 MPa
	Clay	0.3 ~ 1 MPa	0.3 ~ 1 MPa	0.3 ~ 1 MPa	0.3 ~ 1 MPa
Drill hole diameter		0.12 ~ 0.15 m	0.14 ~ 0.25 m	0.14 ~ 0.25 m	0.14 ~ 0.25 m
Drill rod diameter		0.06 m (double-tube)	0.06 m or 0.09 m (triple-tube)	0.09 m (triple-tube)	0.06 m or 0.09 m (double-tube)
Number of nozzles use		1	2	2	2
Jet grouting	material	Binder	Water	Water	Binder
	total pressure	18 ~ 22 MPa	35 ~ 40 MPa	20 MPa	33 ~ 37 MPa
	total flow rate	60 L / min	70 L / min	50 L / min	180 or 360 L / min
Total air pressure		0.6 ~ 0.7 MPa	0.6 ~ 0.7 MPa	0.7 ~ 1.05 MPa	0.7 ~ 1.05 MPa
Binder	total pressure	—	2 ~ 5 MPa	40 MPa	—
	total flow rate	—	140 ~ 180 L / min	190 L / min	—
Rod rotation		<10 rpm	<6 rpm	<6 rpm	2~5 rpm
Withdrawal rate		16 ~ 40 min/ m	16 ~ 25 min/ m	15 ~ 20 min/ m	8 ~ 16 min/ m
Grouting capacity		4.0 m^3 / hr	11.8 m^3 / hr	18.5 m^3 / hr	35.3 m^3 / hr
Binder consumption		0.9 m^3 / m^3	0.9 m^3 / m^3	0.6 m^3 / m^3	0.5 m^3 / m^3
Amount of sludge		1.3 m^3 / m^3	1.8 m^3 / m^3	1.0 m^3 / m^3	0.7 m^3 / m^3

Table 2. Details of jet grouting work at different stages

Work stage	Work days*	Number of grout pile	Length of grout pile	Volume improved
1st stage	38	14	10.24 m	1140.85 m^3
2nd stage	37	10	10.24 m	144.69 m^3
3rd stage	30	14	10.24 m	1140.85m^3

* Work days include traffic re-routing, trial pit excavation, protection and restoration of utilities lines at each stage.

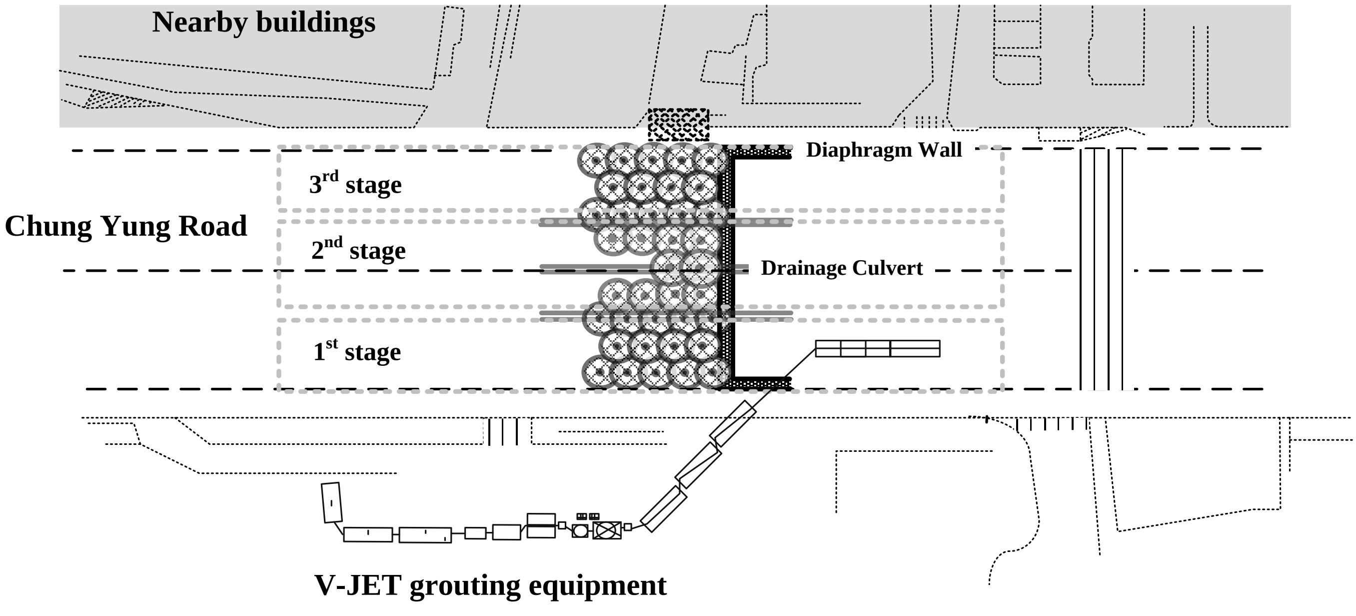


Figure 5. Improvement zones and layout of grouting equipment at different stages

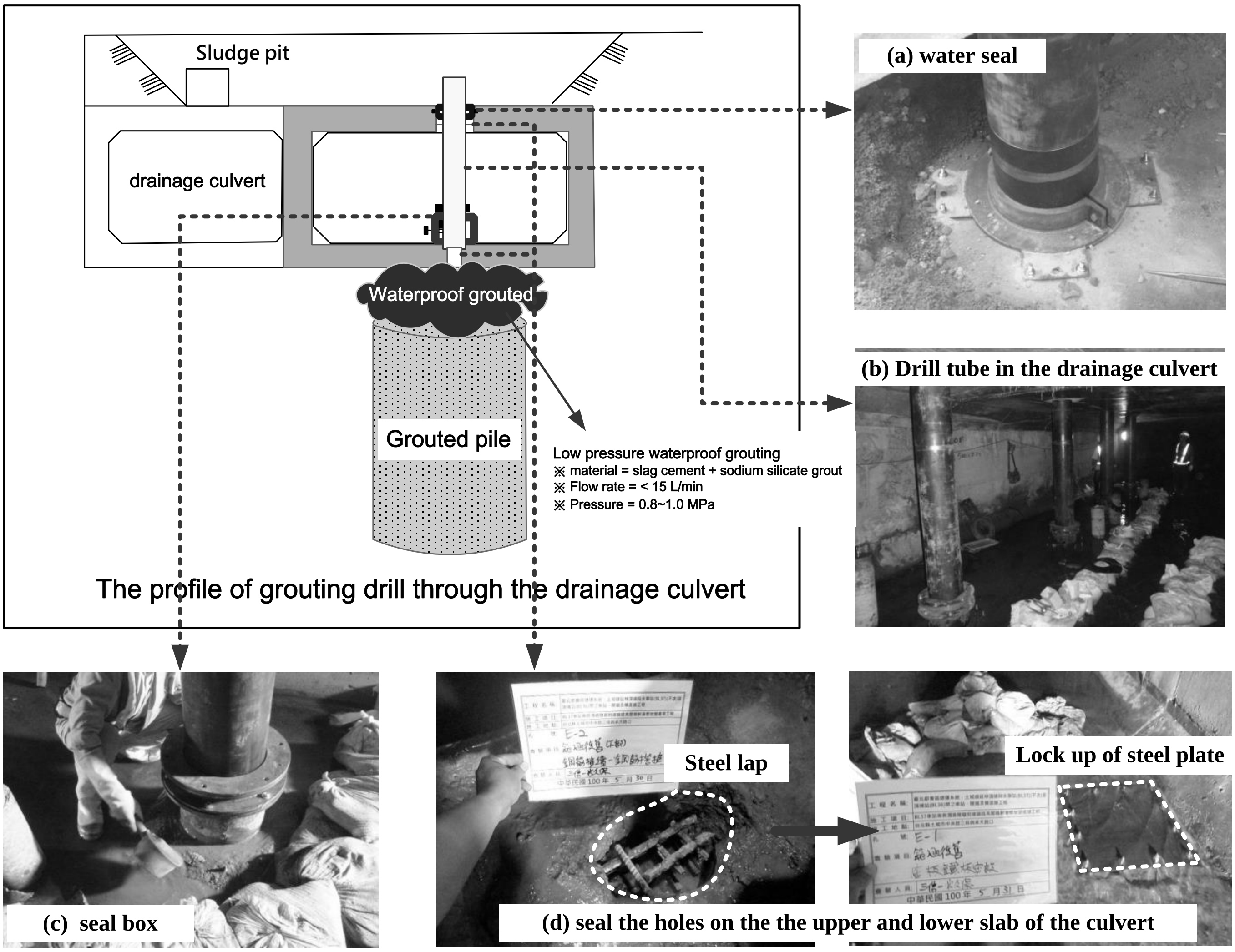


Figure 6. Photos of treatment condition during jet grouting under drainage culvert

4.1 Construction procedure

To maintain the function of drainage culvert during and after the jet grouting practice, the construction procedure taken for this grouting project is illustrated in Figure 6: (1) Excavate the soil cover of the drainage culvert. Position the drill rig. Drill the casing pipe (diameter = 300 mm) through the upper slab and stop at the lower slab; (2) Install the water seal box outside the casing pipe to stop groundwater flowing in from the bottom of the culvert. Replace the casing pipe with a double pipe (diameter = 200 mm) with the monitor mounted at the tip to continue drilling to the design depth; (3) Start jet grouting and withdraw the double pipe. Let the slime overflow through the casing to the surface. Jet grouting stops at some distance below the bottom of the culvert. Withdraw the double tube drilling rod; (4) Insert a 40 mm grout pipe to inject the slag cement + sodium silicate grout at an injection rate of 15 *l*/min and grouting pressure of 0.8~1 MPa to strengthen the soil between the top of jet grout pile and the bottom of culvert; (5) Seal the holes on the upper and lower slab of the culvert with no shrinkage cement and steel plate.

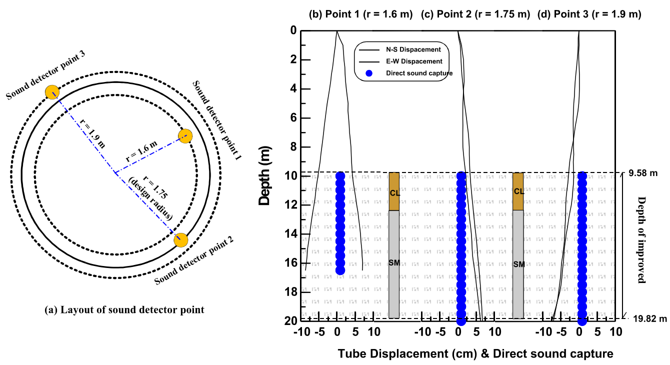


Figure 7. Layout and results of sound detecting test

4.2 Effectiveness of grouting work

To verify the pile diameter constructed by the V-JET method under various grouting parameters and in different soil conditions (silty clay layer and silty sand layer), sound detectors were installed to confirm the pile diameter before the first stage construction was carried out. As Figure 7 demonstrates, the tube and sound detectors were installed at distances of 3.2m, 3.5m, and 3.8m from the grouting point respectively. In general, the drilling alignment of the grouting hole was satisfactory. There was less than 10 cm off the alignment over a drilling depth of 17 – 20 m. All the sound detectors located at different locations could pick up the sound of jet stream. It verified the design pile diameter of 3.5 m, which had been achieved successfully. Using the unconfined compressive strength and the falling head permeability test after the completion of grouting (28 days), 2 grout piles were randomly chosen from 38 grout piles for the quality check. Cored samples were taken from the piles and inspected following the evaluation method for high pressure injection mixing piles proposed by the Japan Society of Civil Engineers (Takashi et al., 2003). The core samples are shown in Figure 8 and all are rated acceptable. Besides, from the consolidated undrained triaxial test run on cored samples, the effective shear strength parameters are increased to $c' = 50 \sim 70$ KPa, $\phi' = 50^o \sim 63^o$ for silty sand layer and $c' = 200 \sim 960$ KPa, $\phi' = 28^o \sim 55^o$ for silty clay layer. Also, the compressive strength and permeability of cored samples can meet the design requirement (Figure 9).

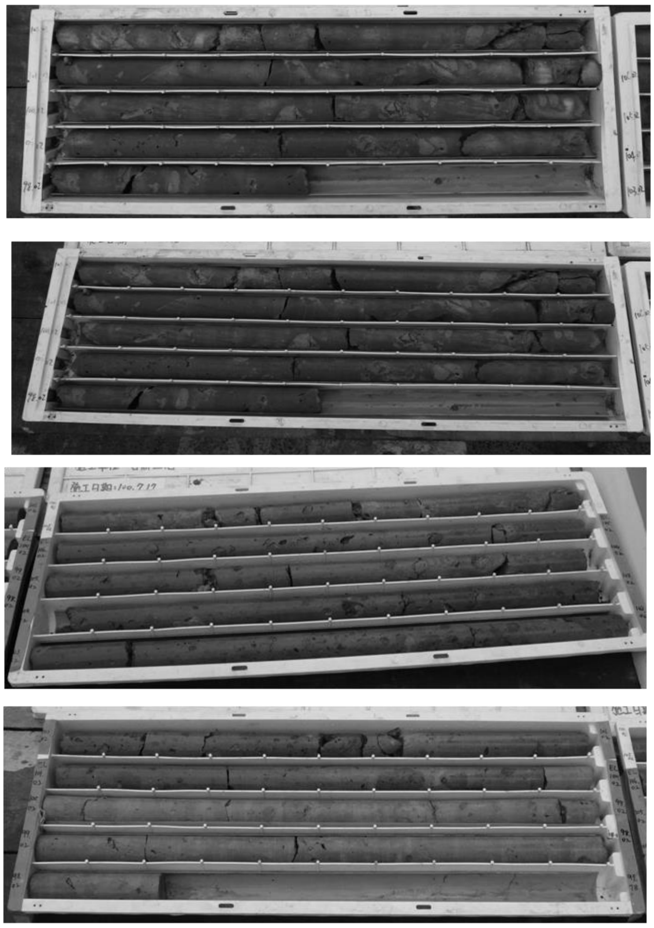


Figure 8. Cored specimens from improved zone

4.3 Cutting work of arrival shield tunnel

While crossing the joint of Tucheng extension Line and the operating Yongning station, the existing 80 cm thick diaphragm wall, 100 cm think headwall, 30 cm thick flood wall and acoustical wall at the station are needed to be broken. To ensure safety of cutting work at arrival of shield tunnel, the shield machines needs to stop work for check up, for coordinates examination, and to be backfill grouting when it approaches in front of arrival shield tunnel (about 20 m before the diaphragm wall of the existing station). The cutting work cannot continue until all conditions are found working normal. As shown in Figure 10 of the cutting block within the improved area, its quality is very similar to the core specimens of Figure 8, which proves a very nice quality of construction that can assure stabilization and waterproof of soil around cutting face of arrival shield tunnelling.

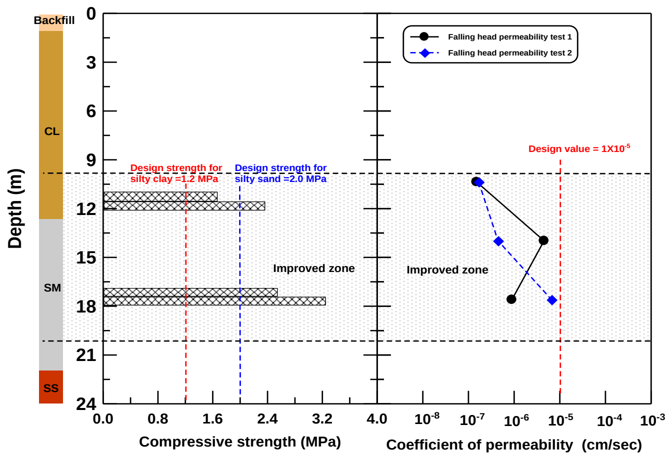


Figure 9. Permeability and compressive strength of grout piles in silty clay/silty sand layer (cured 28 day)

Cutting work does not influence Yongning Station’s normal operation and trains safety. After successful cutting of the existing diaphragm wall and headwall at the station and after the shield machines are removed from operation platform, the shield machines are to be carried to the departure end (Figure 11a). The 1.65 m flood wall and acoustical wall can be broken by chain saw with low vibration and low noise. Figure 11b presents the drilling positions, quantity of cut block and the cut section of acoustical wall. Finally, the cutting work of arrival shield tunnel takes three months to accomplish.

5. CONCLUSIONS

Jet grouting was carried out as the ground improvement work for the arrival of shield machine in Yongning Station of Taipei MRT. Located in between ground surface and shield tunnel, there was a drainage culvert in the way for this grouting project. This paper reports the experience learned from the practice of V-JET grouting project under such a difficult condition. The following conclusions were drawn from the findings of this project:

1) By minimizing the number of grouting holes (either vertical or inclined one), V-JET method can facilitate the grouting job in the congested area or under the busy road. As a result, the quality of the grout piles and the overlapping portion between neighboring piles can be improved.
2) The drainage culvert located between ground surface and shield tunnels was the obstacles of this grouting project. 10 grout holes must drill through the drainage culvert. By proper arrangement of casing drilling, groundwater sealing and jet grouting practice, the function of the drainage culvert can be not influenced during and after jet grouting.
3) The ground improvement project in urban area is often carried out very close to the neighboring buildings. Excess ground movement associated with jet grouting is a common phenomenon.

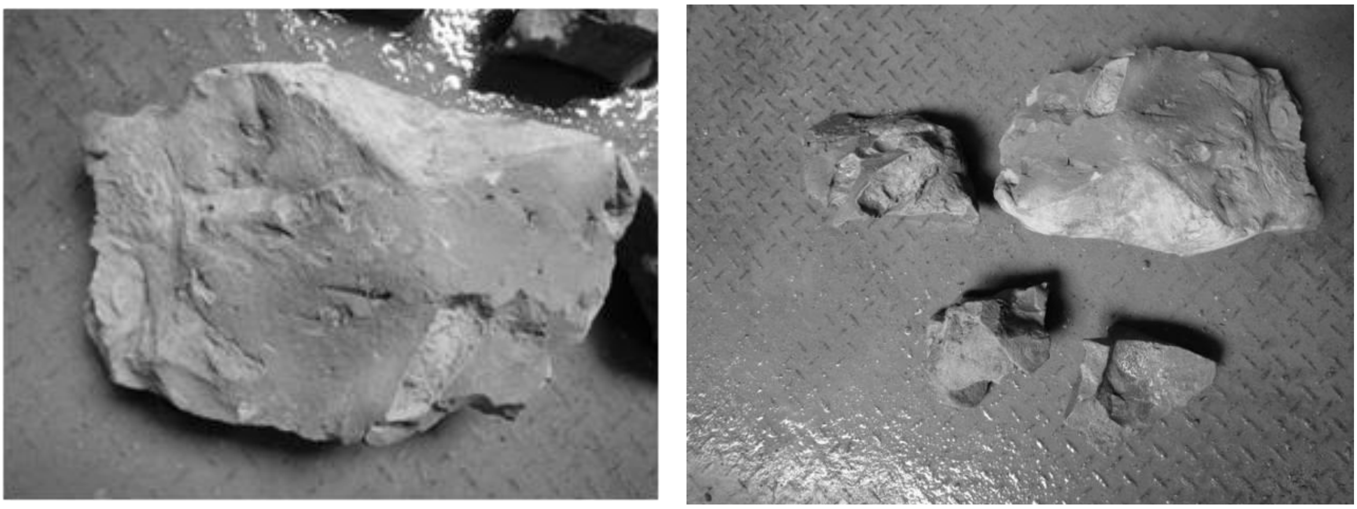
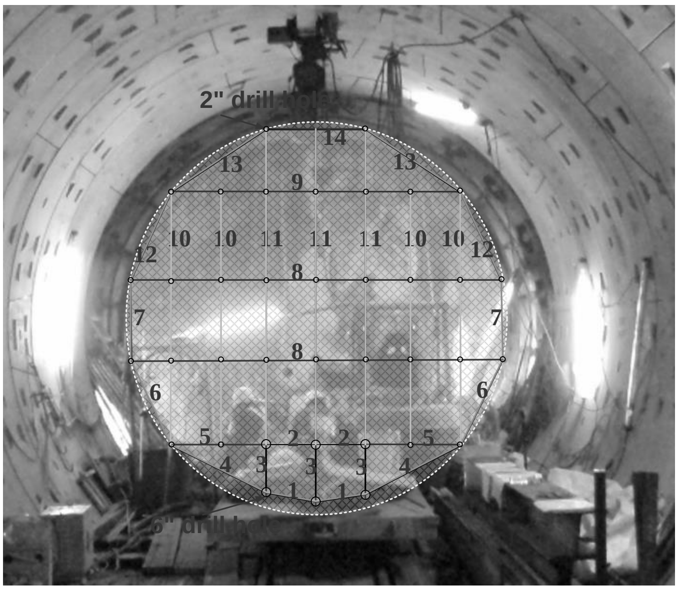


Figure 10. The photo of cut block within the improved area

(a) shield machines and operation platform set off



(b) position drill holes, cut block and cut section of acoustical wall

Figure 11. Shield machines taken apart and the cut section of acoustical wall

6. ACKNOWLEDGMENT

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