INFLUENCE OF GROUND IMPROVEMENT AND CONSTRUCTION MANAGEMENT ON SHIELD TUNNEL EXCAVATION：A CASE STUDY OF KAOHSIUNG MASS RAPID TRANSIT SYSTEM

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***ABSTRACT*:** In this study, Kaohsiung mass transit system is taken as a vase study to investigate the ground improvement. The influences of geological condition, construction management, quality, and working guideline on ground improvement and the impact of construction management on shield tunnel excavation are investigated through unconfined compression strength and P-wave velocity of samples from the laboratory and in-situ. The investigating results indicate that the strength of ground improvement in Kaohsiung is high. The ground improvement mixed design should be a vital factor for ground improvement. In addition, strength of the improved soil is not the sole factor for the quality requirement. The water conductivity is another important factor. More, geologic condition and ground improvement are two important factors for the design of thrust force and torque of the shield machine. The experts should operate shield machine when it passes through the improved ground.

KEYWORDS: Ground improvement, shield tunnel, mass rapid transit system, construction management

1. INTRODUCTION

The Jumbo-jet-special grout method (JGS) is an available technique to improve the ground surrounding the starting and arrival vertical shafts and cross-passage in shield tunnel excavation. The strength of the improved ground must not be too low to stabilize the ground and can not be so high to affect the excavation.

The improved ground exposes to the air after the mirror-face at the retaining wall of the shield tunnel is removed. Poor quality of ground improvement, high groundwater level, and soft ground in a shield tunnel can easily result in un-balanced earth pressure and drainage at the interface of vertical shaft and improved ground. In addition, ground settlement will damage neighboring structures above ground and subsurface structures.

The workability of ground improvement, and geologic condition, and permeability of ground are essential factors to affect the quality of improved ground, except the strength of the ground improvement. The working guideline regulates that the improved ground should fulfill the qualities of unconfined compression strength larger than 2 MPa, permeability small than 10-6 cm/sec, core recovery ratio larger than 85%. The quality requirements can be satisfied if we add 500 kg of cements in each volume of 1 m^3 of injection paste based on the JG-2 mix proportion suggested by Japan jet-grout association (2003). However, poor working management reduces the performance of water-proofing of the improved ground although its strength, permeability, and core recovery ratio remain been satisfied. In this study, several laboratory and in-situ cored samples are conducted to unconfined compression and P-wave velocity tests. The in-situ cored samples coming from the improved grounds at vertical shafts and cross passages of Kaohsiung mass rapid transit system (Kaohsiung MRT system). The testing results are used to investigate the differences between laboratory and in-situ cored samples affected by site conditions, and the acceptance of in-situ cored samples to the working guideline. Then, the study results are expected to be used to evaluate the efficiency of ground improvement and the influences of ground improvement on shield tunneling.

2. LABORATORY AND IN-SITU CORED SAMPLES OF IMPROVED GROUND

2.1 Laboratory Samples

In the laboratory, the ground improved samples are conducted using the following three water/cement ratios (W/C):

Type I: Mortar+ Ottawa standard sand (0%): W/C=0.485,

Type II: Mortar+ Ottawa standard sand (15%): W/C=0.485; Cement : Sand=8.5:1.5,

Type III: Mortar+ standard sand (30%): W/C=0.485; Cement : Sand=7:3

Samples with diameter D=5 cm and height H=10 cm having age of curing of 3, 7, 28, 56, 91, and 180 days are prepared for the laboratory tests. Three samples are used for each curing time of each mix proportion types of W/C. Therefore, totally 54 samples are conducted in this study. Ultra-sonic velocity and unconfined compression strength of each sample are measured.

The expansive of cement mortar is investigated based on ASTM C806-95. The samples with cases II and III of specific age of curing of 28, 56, and 91 days are crushed, dried out, and grinded to the fineness of 4000 to 4200 cm2/g. Then, the powder of each W/C ratio in each curing time is used to have six new samples (Types 2 and 3 with specific curing times) with water/solid ratio=0.485. The volume change of each new sample is measured at each age of curing of 1, 2, 3, and 4, 5, 6, as well as, 7, 14, 21, and 28 days to evaluate the expansive of cement mortar.

2.2 In-situ Cored Samples

Samples from six ground improved locations in Kaohsiung MRT sites are taken in this study. Three samples with diameter D=5 cm and height H=10 cm are taken from the upper, middle, and lower parts of each core. Then, ultra-sonic velocity and unconfined compression strength of each core are measured in this study.

3. TEST RESULTS

3.1 Laboratory Samples

3.1.1 Unconfined compression strength

Fig. 1 illustrates the relation between unconfined compression strength qu and the age of curing A. The unconfined compression strength increases with the increasing age of curing in every mix proportion. In addition, the relation can be shown using Eq. 1 with R2>0.97.

$$q_u = C + \ln A \times D \qquad (1)$$

where, C indicates the unconfined compression strength in the early time. D shows the increase rate of unconfined compression strength to the age.

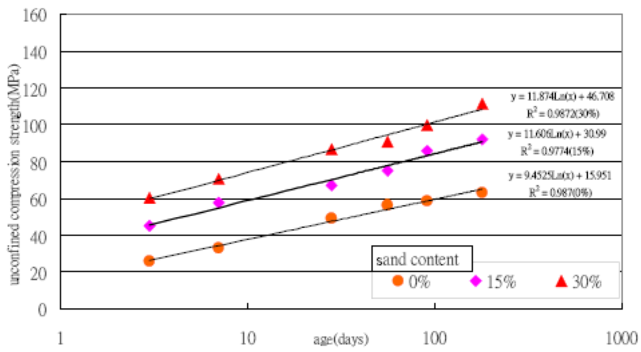

Fig. 1 Unconfined compression strength versus age

The values of C and D under different mix proportions are listed in Table 1. It is obvious that the value C increases with and increasing sand content, indicating that the ground improvement has higher quality when the sand content increases. In addition, the D in Type I is smaller han the ones in Types II and III. More, the increase of D with sand content from 0 to 15% is larger than the one with sand content from 15% to 30%.

Table 4 The C and D under different mix proportions

Sand content (%)	C (MPa)	D (MPa/day)
0	15.95	9.45
15	30.99	11.60
30	46.71	11.87

3.1.2 P-wave Velocity

P-wave velocity is a useful index that is widely used in nondestructive testing method. The velocity can be used to evaluate the cracks and pores in a sample and is expected to be correlated well with the unconfined compression strength of a sample. The testing results show that the measured P-wave velocity (Vp) and the unconfined compression strength (qu) of each sample with different mix proportions perform to be a linear relation as shown in Fig. 2 and can be demonstrated as the following Eq. (2) with R2>0.96.

$$V_p = A + B \times q_u \tag{2}$$

where, B is the increase rate of P-wave velocity with increasing unconfined compression strength. The value equals 9.79 at the sample with sand content=0% and is larger than the B in other mix compositions. The high density of the sample with sand content=0% can be due to the finer grain size than that in other mix compositions. The values of B with sand contents of 15% and 30% are close to each other, indicating that the sand content has insignificant impact on the increase rate of P-wave velocity with increasing unconfined compression strength.

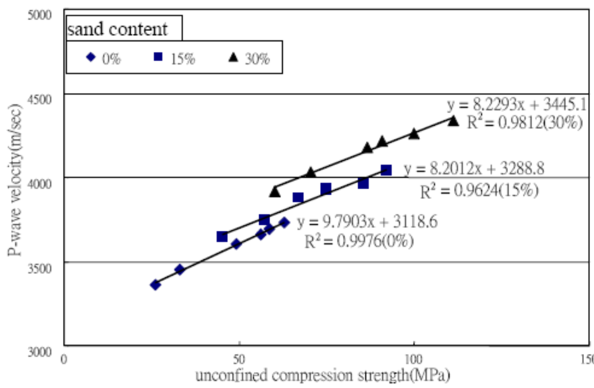

Fig. 2 Unconfined compression strength versus P-wave velocity (Laboratory samples)

3.2 Volume Expansion

In Fig. 3, the maximum volume expansion of samples with different mix proportions and age is 0.035%, which is below the allowable value of 0.8%. In addition, the expansion of secondary hydration decreases after the age of 7 days. The expansion of secondary hydration at the age of 28 days has similar trend, but the value changes with different sand contents. The difference of expansion with different sand contents is still remarkable at the age of 56 days. However, the differences of expansion of secondary hydration under different sand contents become insignificant after the age of 91 days.

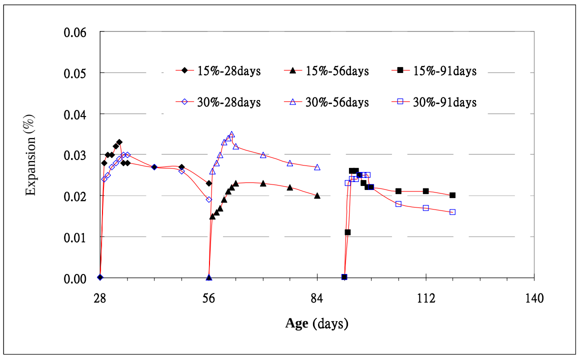

Fig. 3 Expansion of secondary hydration

3.3 In-situ Cored Samples

3.3.1 Unconfined Compression Strength

Fig. 4 illustrates the unconfined compression test results of in-situ ground improved samples taken from the sandy ground of Kaohsiung MRT. The unconfined compression strengths of the in-situ cored samples distribute in the range of 2 to 38 MPa. The strengths of the in-situ cored samples have large varieties and are larger than the design strength of 2 MPa. The exceeding torque in the shield excavation easily produces cracks when it is excavated in the inhomogeneous improved ground.

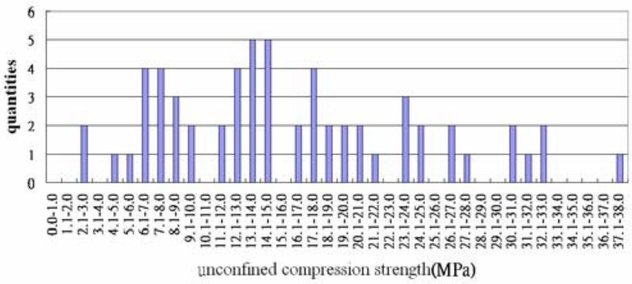

Fig. 4 qu of in-situ cored samples (Sandy ground)

On the other hand, Fig. 5 shows the unconfined compression testing results of the in-situ cored samples of ground improvement taken from the silty ground in Kaohsiung MRT. The unconfined compression strengths of the samples distribute in the range of 2 to 35 MPa, but most of them are below 10 MPa.

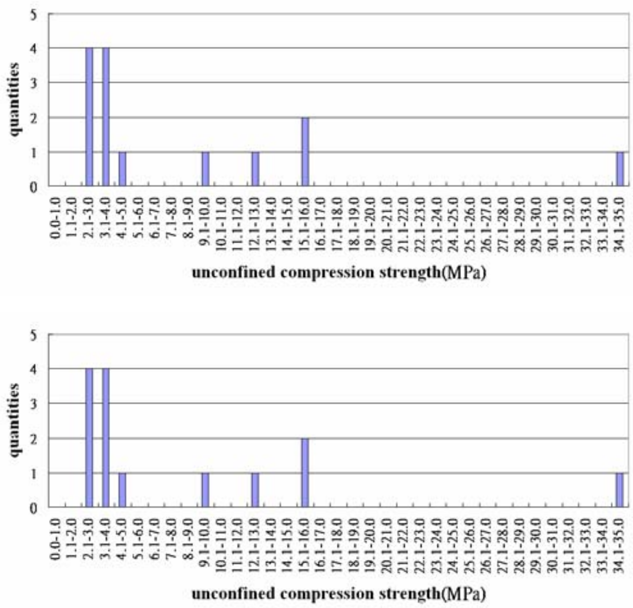

Fig. 5 Unconfined compression strengths of in-situ cored samples (Silty ground)

In Fig. 6, 64% of the investigated samples with silty ground and 17% of the samples with sandy ground are in the idealized strength of 2 to 7.5 MPa. In addition, the strengths of 21% samples with silty ground and 44% with sandy ground are classified to be high strength samples (>15 MPa). However, the unconfined compression strengths of improved ground with JG-2 are distributed in the rage of 2 to 6 MPa, which correlate well with the designed strength, when in-situ cored samples were taken in Japan. The testing results imply that the JG-2 is suitable for the silty ground of Kaohsiung in ground improvement but not sandy one. The mix proportion of JG-2 should be adjusted to prevent from the difficulty of shield tunnel excavation in the zone with ground improvements.

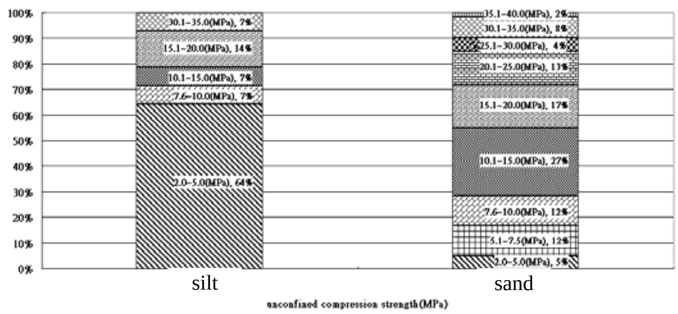

Fig. 6 qu distribution of in-situ cored samples at Kaohsiung

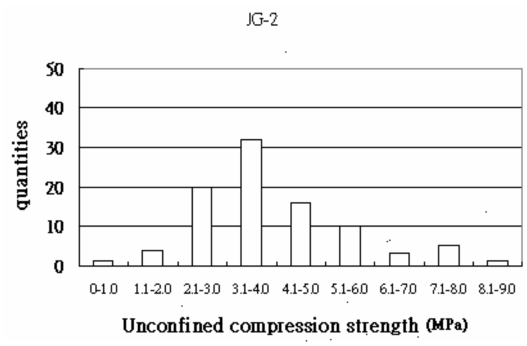

Fig. 7 qu distribution of in-situ cored samples in Japan

3.3.2 P-wave Velocity

Fig. 8 demonstrates the relation between P-wave velocity and unconfined compression strength of the in-situ cored samples taken from the upper, middle, and lower parts of a borehole. Eq. (2) can be also applied to simulate the relation with R2>0.98.

The depth is taken as a parameter and is divide the depth GL-10 to 35 m into 5 sections to investigate the relation between P-wave velocity and unconfined compression strength of each section. Fig. 9 shows the testing results of in-situ cored samples at the depth from 15 to 20 m. A linear relation is obtained. The values of intercept A and gradient B in Eq. (2) of each section of depth are demonstrated in Figs. 10(a) and 10(b).

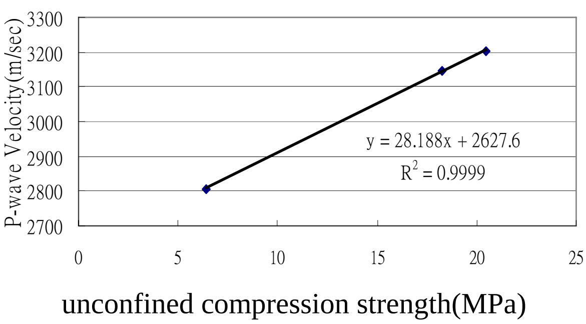

Fig. 8 qu versus P-wave velocity (in-situ cored samples)

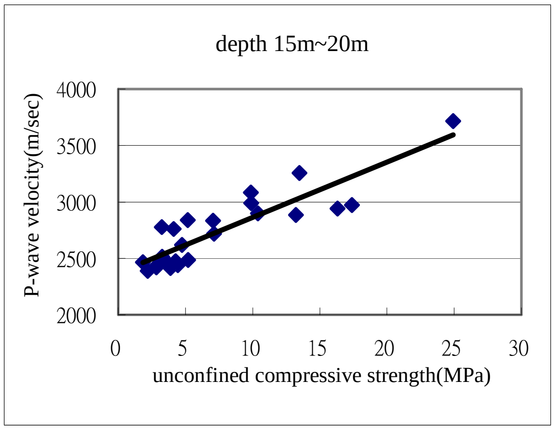

Fig. 9 unconfined compression strength versus P-wave velocity at depth 15 to 20 m (in-situ cored samples)

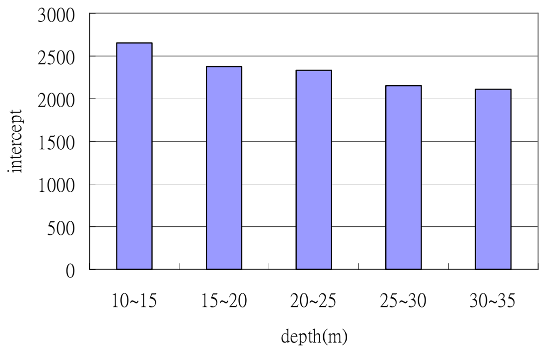

Fig. 10(a) The intercept (A) of Eq. (2) at different depths

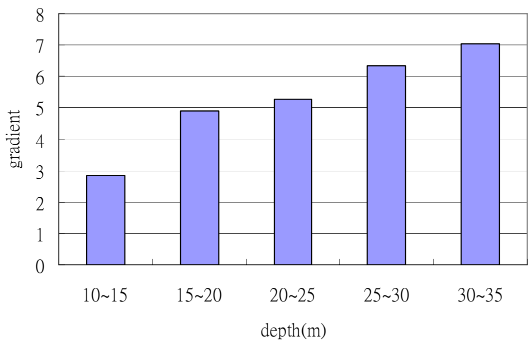

Fig. 10(b) The gradient (B) of Eq. (2) at different depths

Physically, the intercept A indicates the index related to pores in ground improvement under stress release state. The gradient B represents the void congestion speed under loading. In Fig. 10, the value A decreases as the increasing depth. On the contrary, the B value increases as the increasing depth. The testing results indicate that the pore increase causes the decrease of unconfined compression strength at the depth. However, the void congestion speed increases.

Effective void ratio test is conducted to the samples obtained from in-situ boreholes to validate the voids in the improved ground. The depth versus effective avoid ratio is demonstrated in Fig. 11, showing that the effective void ratio increases with the increasing depth. Therefore, the poor ground improvement is obtained at the depth.

The ground is mainly consisted of silty sand with low plasticity and sandy silt. It is easily be weaken and liquefied because of ground disturbance. The high pressure water in JSG washes out the fine grains of the silt and decrease the number of contacts among soil particles to generate weak soil structure. Therefore, flowing sand and groundwater drainage are often occurred because the decreasing ground strength and producing voids in the ground due to excavation disturbance.

4. INVESTIGATING THE GOVERNING FACTORS OF GROUND IMPROVEMENT QUALITY

4.1 Local Geology and Geography

Kaohsiung is geographically classified to be an alluvial plain at the coastal area. Salinity and tide are two governing factors to impact local hydrology underground, working technique selection, and the quality of ground improvement.

In addition, high pressure injection technology such as JSG is usually applied to ground improvement. However, it is not a perfect technology especially in the saturated loose sandy ground because the ground disturbance due to shield causes soil liquefaction, collapse, erosion, and flow.

More, the diameter and continuity of high pressure injection pile change in different soil layers. In addition, the secondary remove of mirror must be conducted artificially to avoid drainage and sand flow caused by the damage of improved ground due to large vibrations induced by excavation machine. In high static pressure zone or the disturbance of pulse injection are expected to enlarge the flow path of in improved ground. Disasters may arise during underground excavation if we can not stop water drainage in time.

Next, insufficient and unspecified site investigation unable engineers to design the shield tunnel appropriately based on local geology. The soils at Yancheng and Sitzuwan in the west Kaohsiung are silty sand without self supportability. The soil characteristics are hardly determined without detail site investigations.

4.2 Contract and Construction Management

The Kaohsiung MRT project is contracted by BOT. Therefore, the planning, investigation, and contracting are conducted based on the cost of the construction and the engineers in a construction company must take responsibility of planning, design, and construction supervision by them-self. Therefore, the quality of the construction is expected to be low because it only satisfies the lowest requirement of the working guideline.

Next, inappropriate protective construction during shield tunnel excavation coming from short construction period and insufficient construction budget result in construction accidents.

More, Taiwan-Japan JV company dominates the construction in Kaohsiung MRT project. The personnel expanse of Japanese engineers is high. In addition, they usually insist to use Japanese construction technique with expansive construction materials. Therefore, the project managers from

Taiwan and Japan usually have irreconcilable conflict in the cost management.

There is a gap of professional capabilities between Taiwanese and Japanese engineers. The Japanese engineers often can not get sufficient support from Taiwanese workers. Therefore, some Japanese companies must spend extra personnel expense and send supervisors from Japan to guide Taiwanese works. In addition, professional interpreters are required for the technical communications during constructions.

Some site supervisors coming from Kaohsiung Mass Rapid Transit (KMRT) and Kaohsiung Rapid Transit Corporation (KRTC) have insufficient professional knowledge. They are also busy in paper work and are unable to supervise and direct the construction project.

4.3 Requirements of Construction Quality and Construction Guideline

The BOT contract conducting in Kaohsiung MRT project generates problems in construction management because most officers assigned by the proprietor are freshmen in MRT project. In special construction conditions, the officers must agree with the requirements from contractors without technical management.

In addition, the mix proportion suggested by Japanese guideline is applied to the ground improvement in Kaohsiung. High unconfined compression strengths of the improved ground is obtained because of the difference of geological condition. Some engineers even misunderstand that high strength of improved ground equals high improvement quality. The large variation of unconfined compression strength in samples cored from improved ground implies poor mix proportion control, geologic realization, and construction technology selection.

More, the construction guideline of Kaohsiung MRT regulates that the diameter of the improved pile surrounding the starting and arrival shafts must be less than 1.6 m for JGS technique. The JGS technique attaches specified nozzle as shown in Fig. 12 in front of the drill rod and uses high pressure water to excavate the ground to a specified depth. Then, inject the mortar and mix the neighboring soils to produce cylinder improved pile. The length and the angle of the nozzle are governing factors to generate theoretical injection. Short nozzle produces disturbance during injection. Reducing the size of the outlet to generate high pressure injection is not unique importance but correctly forms desired water-column as shown in Fig. 13(a). Poor quality or damage of nozzle cause water-jet dispersion during injection as show in Fig. 13 (b) and is unable to excavate soils appropriately.

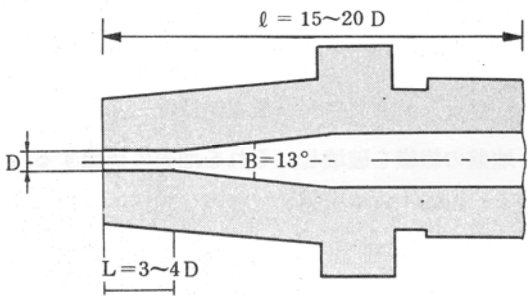

Fig12 section of injection nozzle

The stiffness of the ground (N-value) affects the diameter of the improved pile. Too many cements are used in the stiff ground if the construction guideline regulates the pile diameter must be less than 1.6 m.

Different in-situ improved grounds between the reality and the evaluated one are obtained due to the non-homogeneous ground improvement and the replacing RQD to sampling rate. These reasons make engineers unable to appropriately evaluate the water-proofing of the improved ground. The strength requirement of the low limit of the improved ground but not the high limitation makes shield tunnel hard to appropriately excavate in the improved ground. Besides the strength, the quality of water-proof of the improved ground is another crucial requirement to the improved ground. Therefore, the water test in shield tunnel excavation is an essential test to safeguard the constructions.

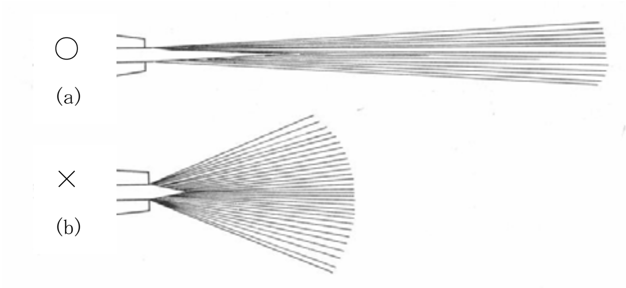

Fig13 Jet of nozzle

5. CONCLUSIONS

The mix proportion JG-2 suggested by Japan Jet-grout Association is suitable for ground improvement of the shield tunnel construction in Japan. However, the quality of the improved ground varies significantly place to place in Kaohsiung MRT project when JG-2 is applied to the ground surrounding to vertical shafts and cross-passage. Different soil characteristics between Japan and Kaohsiung are expected to be a main reason to cause the differences.

The strengths of most samples cored from the improved ground neighboring to the starting and arriving shafts are higher than the design value of Kaohsiung MRT project. Therefore, adjusting the performance and the operation of the shield machine are important in the tunnel excavation.

The impact of improved ground to the shield tunnel excavation is highly related to the experiences of in-situ engineers, local geological conditions, and the grouting technology, as well as, appropriate performance and operations of shield tunnel machine. Therefore, it is very difficult to numerically evaluate the impacts of ground improvements on the shield tunnel because of the difficulty of involving governing factors to the numerical simulations.

Most of the accidents happened in the shield tunnel excavation can be avoided if contractor realizes local geotechnical characteristics by detailed site investigations and the proprietor assigns experienced supervisors to join the project.

It is essential to investigate new mix proportion or suitable construction guideline for the ground improvements conducted to the grounds adjoining to the vertical shafts and cross-passage of shield tunnel excavations in Kaohsiung.

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