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## Geotechnical optimization in underground construction

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**ABSTRACT:** Geotechnical optimization in underground construction will be presented in the keynote speech. It includes optimization in deep excavation such as pressurized grouting in soil nailing, pre-stressed soil nailing, optimization of soil nailing design considering three failure modes and pressurized compression anchor; optimization in tunnelling such as innovation in UAM, utilization of non-destructive testing, and risk methodology in mechanized tunneling, etc.

### 1 INTRODUCTION

Uncertainties cannot be avoided in underground construction; conservative design is a usual practice to take the geotechnical uncertainties into account. As a keynote speech, I will introduce some of our efforts to optimize the design and construction of underground structures in a geotechnical view point, both in deep excavation and in tunnelling.

### 2 OPTIMIZATION IN DEEP EXCAVATION

#### 2.1 *Pressurized grouting in soil-nailing*

Soil nailing is a widely used soil reinforcement technique adopted for deep excavations instead of strut system and/or anchored structures. It enhances the shear resistance of soil and the skin friction at the interface between the grout and soil mass.

Although most grouting practice has been performed by gravitationally filling the voids of soil formation without pressurization, pressurized grouting has been frequently adopted in a soil-nailing system that is widely used to improve stability.

Seo et al. (2012) deal with a series of pilot-scale chamber tests performed on four different granite residual soils to evaluate the effect of pressurized grouting on the soil-nailing system. When grout is injected into a cylindrical cavity in the soil mass, the pressure exerted around the cavity perimeter initially increases with time up to a peak value, and then gradually decreases to a residual stress. The pressure reduction may result from the seepage of water originally retained in the grout paste into the adjacent soil formation. With the application of pressurized grouting, in-situ stresses can be increased by about 20% of the injecting pressures during the experiments. In order to develop a desirable residual stress in a soil-nailing system, it is necessary to select an appropriate minimum injection time to which the grout pressure should

be maintained. The required minimum injection time increases with an increase in either the fine-grain content or the injection pressure. Moreover, a series of in-situ pullout experiments has been performed on soil-nailing systems, using both pressurized grouting and common gravitational grouting in order to compare the pullout loads of both cases and to verify the effectiveness of the pressurized grouting on the soil-nailing system.

A schematic of the soil-nailing system using pressurized grouting is shown in Figure 1, which consists of 2.0 m of grouted nail, 0.5 m of packer and 0.5 m of free body. In contrast, a total length of 3.0 m was chosen for the soil-nailing system using gravitational grouting. The pullout load of soil-nailing using pressurized grouting is about 36% higher than that of soil-nailing using gravitational grouting (see Fig. 2). This is attributed to the additional compaction of soil by cavity expansion and to an increase in the residual stress and in the dilatancy angle by pressurized grouting. The field experimental results have been verified with analytical solutions by estimating the dilatancy angle from the pressurized grouting tests.

#### 2.2 *Pre-stressed soil-nailing system*

The resistance of soil-nailing is mobilized when and only when ground movement occurs to a certain extent. For this reason, it is difficult to prevent a portion of initial displacement.

The author's field experience indicates that a governing factor in the soil-nailing design has frequently been the yield load of the steel bar rather than the pullout resistance of the ground. Therefore, in this study, a prestressed soil-nailing is introduced to enhance the integrated (or combined) yield load of reinforcing components. This new system is equipped with two reinforcing components: a steel bar for soil-nailing and two PC strands connected to the anchor body. A schematic view of load transfer for the prestressed

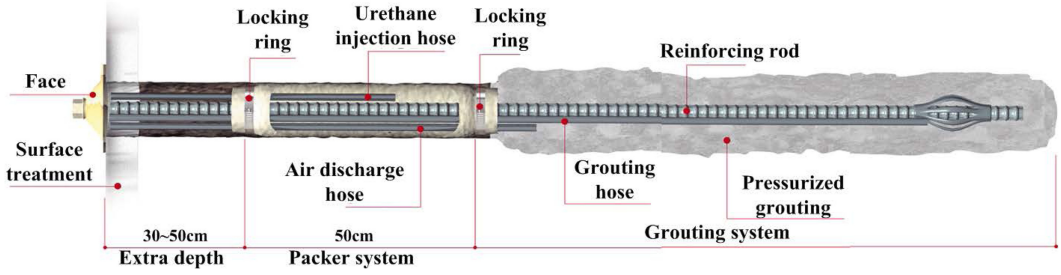


Figure 1. Assembly of the soil nailing using pressurized grouting.

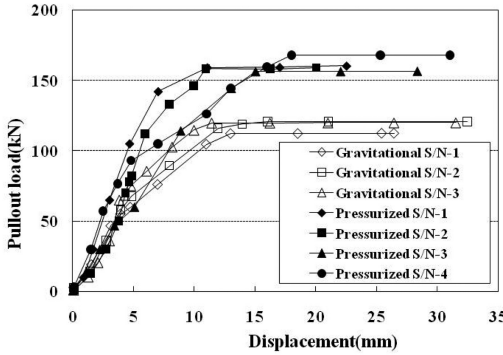


Figure 2. Load-displacement curve.

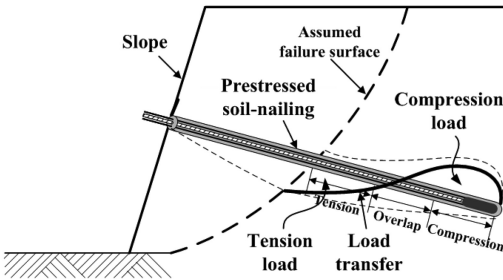


Figure 3. Load transfer of prestressed soil-nailing.

soil-nailing is shown in Figure 3. The steel bar with relatively less elongation yields earlier than the PC strands. Therefore, the yield stains of the two components should be matched to maximize the design load (capacity) of the prestressed soil-nailing. To achieve this condition, the PC strands need to be prestressed before applying pullout load. In this study, the load transfer mechanisms of the soil-nailing, compression anchor, and prestressed soil-nailing were developed on the basis of the skin friction theory and the load transfer theory (Seo et al. 2014). Field pullout tests were performed to identify the in-situ load transfer mechanism and these results were compared with theory. In addition, the prestress level required to maximize the pullout loading capacity was evaluated and compared with those obtained from the field tests. The prestressed soil-nailing is found to significantly increase its integrated (or combined) yield load, provided that

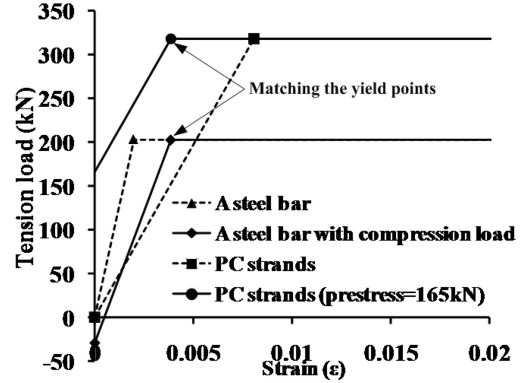


Figure 4. Load-strain curves for a steel bar and PC strands with prestress.

the prestress is timely applied to the system, because the prestressed soil-nailing can enhance the resistance of a steel bar (see Fig. 4).

### 2.3 Optimization of soil-nailing design considering three failure modes

In the current soil nailing design practice, only the pull-out failure and the shear failure are considered as the main design factors. However, in the deep excavation site, multi-face excavation is executed rather than full face excavation, and face failure can therefore occur in each excavation step due to the decrease of confining pressure on the excavation face, during the top-down excavation.

Therefore, it is necessary to include face failure as the main design factor in the slope design (see Fig. 5). Seo et al. (2014) theoretically verify the mechanical behavior of face failure as well as pullout failure and shear failure. The constrained conditions for each failure mode are defined, and the optimization of soil nailing design is proposed on this basis. The design variables considered for the three failure modes are the bonded length of nail, the number of nails, and the prestress (see Fig. 6). These three design variables are estimated from the optimization design procedure proposed in this study considering constrained conditions. As the optimization design procedure of soil nailing proposed in the paper considers not only the

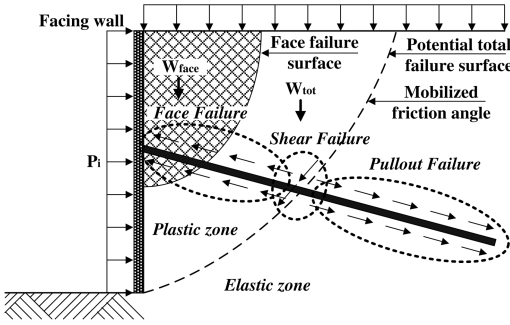


Figure 5. Three failure modes.

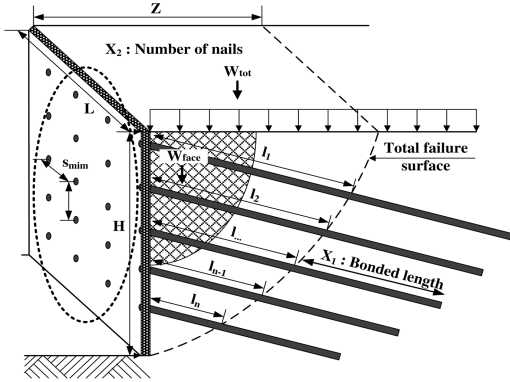


Figure 6. Design variables in optimization of soil nailing design.

pullout and shear failures but also face failure, it could be amore satisfactory design procedure in the actual field.

#### 2.4 Pressurized compression anchor

Various types of ground anchors are frequently used as a tieback during excavation. In cases where the ground anchors are installed adjacent to the existing buildings or facilities in urban areas, there is an increasing use of the compression ground anchor which can be removed from the ground after construction to avoid violating adjacent boundaries. In designing the compression ground anchor, the pullout resistance is a key parameter which varies according to the installation method, soil dilation, roughness of anchor surface, shear strength of the soil, group effect, grout injection method, and so on.

Lee et al. (2012) evaluates the effect of pressurized grouting on pullout resistance of a compression ground anchor according to the soil types by performing both the pilot-scale laboratory chamber tests and field tests. Not only the cavity expansion theory but also the grout penetration theory are adopted and are compared with experimental test results to investigate the effect of pressurized grouting on the enlargement of the anchor body diameter. A grout consolidation model in radial direction is also adopted and compared

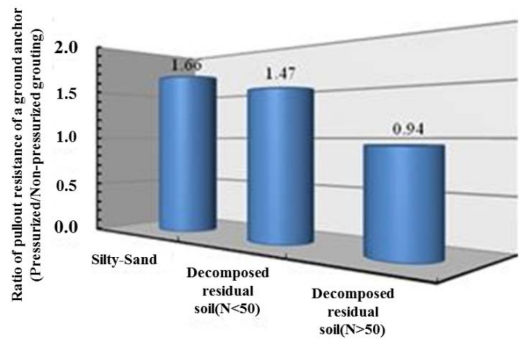


Figure 7. Increase of pullout resistance due to the pressurized grouting.

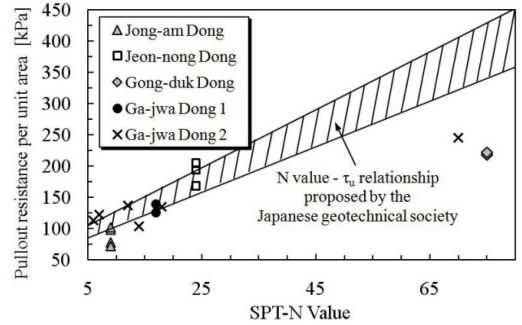


Figure 8. Relationship between SPT- $N_{60}$  value and pullout resistance per unit area.

with experimental test results to determine the required injection time of the pressurized grouting.

The laboratory test results showed that the enlargement of the anchor body diameter estimated theoretically by combining the cavity expansion theory and grout penetration characteristics matches reasonably well with that obtained from experiments. The required injection time as a function of the coefficient of permeability of the ground was proposed. The results of a series of field anchor pullout tests showed that the effect of pressurized grouting is more prominent in a softer ground with a smaller SPT-N value for both the increase in the anchor body diameter and the pullout resistance. The pressurized grouting effect in comparison with gravitational grouting was found to be almost zero if the SPT-N value is more than 50 (see Fig. 7). Based on experimental results, a new equation to estimate the pullout resistance as a function of the SPT- $N_{60}$  value was proposed and shown in Figure 8.

### 3 OPTIMIZATION IN TUNNELLING

#### 3.1 Innovation in UAM

The umbrella arch method (UAM) has been used widely to secure short-term stability during tunnel construction by preventing collapse of the tunnel face

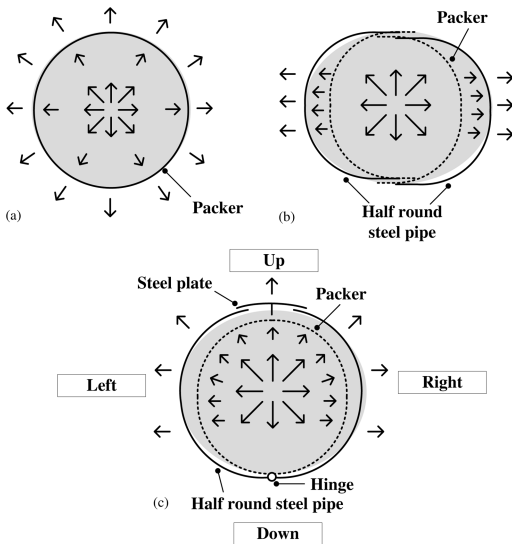


Figure 9. Three types of inflatable pipes: (a) all-directional; (b) two-directional; (c) three-directional.

under unfavorable ground conditions such as soil with poor self-standing and/or weathered soil with shallow cover.

For the analysis of the UAM reinforcement effect, the concept of the equivalent material properties considering the reinforcement effects from the surrounding ground, the inserted steel pipes, and the grouting material injected through the pipes, is generally adopted as an integrated concept. Therefore, the determination of the equivalent material properties is greatly influenced by how far the designer sets the range to improve the ground with the compressed grouting or the range to form the grouting bulb. Through laboratory and field experiments, Kim et al. (2009) studied the changes in the generated volume of the grouting bulb and the material properties of the surrounding ground caused by the UAM under conditions from residual soil to highly weathered rock. The results showed that the cement barely penetrated into the ground around the pipes and consequently the grouting bulbs were generated only inside the pipes and boreholes. Therefore, the improvement in material properties of the surrounding ground is negligible and the reinforcement effect in the UAM is created only by the stiffness of the steel pipes and the cement columns formed inside the steel pipes and between the pipes and boreholes. In this respect, it is necessary to increase the reinforcement effect of the inserted pipes to maximize the UAM effect.

This study suggests a new tunnel auxiliary reinforcement method, the pressure-induced inflatable pipes method (PIM), which applies cavity expansion theory to increase the reinforcement effect of the inserted pipes while following the mechanism of UAM. As shown in Figure 9, three types of inflatable pipe (all-directional, two-directional, and three-directional pipes) were devised according to their

inflation direction under pressure and their reinforcement effects were analyzed.

To compare the reinforcement effects of the three inflatable pipes, a numerical analysis was carried out. This showed that the three-directional inflatable pipe had the best tunnel reinforcement effect by supporting the released stress with its upward inflation pressure and redistributing the stress. Therefore, the three-directional inflatable pipe was selected as the optimum type of pipe.

When the reinforcement effect of PIM using the three-directional inflatable pipe was analyzed with the concept of equivalent internal pressure, the equivalent internal pressure ultimately depended only on the magnitude of the inflation pressure of the inflatable pipe regardless of the magnitude of overburden pressure.

To verify the relative tunnel reinforcement effect of PIM experimentally, a trapdoor test was carried out, both for PIM using the selected three-directional inflatable pipe and for UAM using the no-pressure pipe. The tests showed that the three-directional inflatable pipe imposed a smaller stress than UAM on the trapdoor plate for the same displacement. This means that PIM has a less released overburden pressure when the same tunnel internal displacement occurs. Therefore, the concept of PIM with the three-directional inflatable pipe is a very effective tunnel reinforcement method.

### 3.2 Utilization of non-destructive testing for rockbolt integrity assessment

When constructing underground structures, rock bolts and shotcrete play crucial roles in the development of ground control systems. Furthermore, rock bolts are an essential component of conventional tunneling and single-shell methods. Rock bolts are installed in a rock mass and are fixed with grouting. When rock bolts are embedded in a rock mass on the crown of a tunnel, the grouting material may flow out of the hole because of gravity. Thus, there is always a concern of a non-grouted zone at the upper end of the installed rock bolts.

Pull-out tests (destructive methods) have been traditionally performed to evaluate the presence defects, as well as the capacity of rock bolts. Pull-out tests, however, are known to be a time-consuming, expensive, and inaccurate method for determining the quality of the grout.

Yu et al. (2013) developed a reflection method for the evaluating the non-grouted ratio of rock bolts in the field. Experimental studies were carried out with three types of rock bolts: non-embedded rock bolts that were only grouted along the steel bars; rock bolts embedded in concrete columns; and rock bolts embedded in a rock mass in the field.

The generation and measurement systems for the guided ultrasonic waves adopted in this study are shown in Figure 10. The system includes generation, detection, and recording systems for guided ultrasonic waves. The source and the receiver for the generation

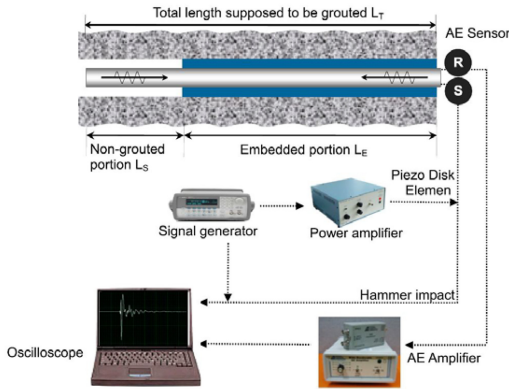


Figure 10. Measurement systems.

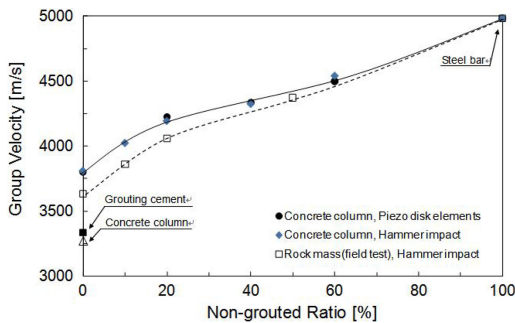


Figure 11. Group velocities versus non-grouted ratios of the rock bolts embedded in rock masses.

and detection of the guided ultrasonic waves were installed at the same location: the head of the rock bolt.

The measured guided waves are analyzed using wavelet transforms. The peak magnitudes of the wavelet transform are used for the group velocity calculations. Although piezo disk elements are sufficient as sources for non-embedded rock bolts and rock bolts installed in concrete columns, they do not provide sufficient energy in the field. However, a hammer impact with a center punch can generate guided ultrasonic waves with enough energy to evaluate the non-grouted ratio in rock bolts embedded in a rock mass. The group velocities of the guided ultrasonic waves increase with increasing non-grouted ratio. This study demonstrates that the suggested hammer impact method is effective for the evaluating the nongrouted ratio of rock bolts in the field (see Fig. 11).

### 3.3 Risk analysis

#### 3.3.1 Risk analysis applicable to mechanized tunnelling

The shield tunnel boring machine (TBM) system in which a metallic cylinder assembly is pushed forward with a minimum disturbance to the original ground conditions has been well recognized as a promising

technology for constructing tunnels with a high level of safety during excavation and lining.

In recent years, the TBM method has been widely adopted in numerous tunneling projects worldwide because this mechanized tunneling method is technically sensible, environmentally friendly with minimized noise and vibration, and presents an economical alternative to the conventional tunneling method, in particular in unfavorable ground conditions for long drives with high advance rates.

However, the TBM is less adaptable in coping with unexpected obstructions on the way of driving because this system can move backward only with great difficulty, which leads to delays or stoppages and an increase in construction costs. Therefore, the potential risk factors and their consequences in both the design and construction stages need to be predicted for TBM tunnel projects, and relevant measures need to be taken against each risk, so that all the risks are systematically managed to minimize the various and complex uncertainties of a TBM tunnel project.

For this purpose, Hyun et al. (2014) categorizes the possible risk of undesired events during TBM tunneling into cutter-related malfunction, machine blockage or hold-up, mucking problems that hinder transporting excavated materials, and segment defects. Each risk factor is classified into one of three representative causes—unpredicted geological factors, design errors and construction/management errors—to constitute a fault-tree (FT) set. Figure 12 shows an example of risk factors associated with cutter-related malfunction. Along with the FT for risk factors, a systematic approach is proposed to quantify the probability of risk occurrence and the consequences of major risks for shield TBM tunneling by adopting a fault-tree analysis (FTA) and an analytic hierarchy process (AHP). The risk evaluation method proposed in this study was verified by comparing the risk occurrence frequency with real downtime data obtained from an actual shield TBM project. In addition, risk evaluation could be used to support decision making during design and construction with the aim of trying to avoid most of the undesirable events.

#### 3.3.2 Event tree analysis applicable to underwater tunnel

Hong et al. (2009) analyzes the risk probability of an underwater tunnel excavation using an earth pressure balance (EPB) type Tunnel Boring Machine (TBM). An event tree analysis (ETA) has been applied to quantify the risk at the preliminary design stage of the tunnel. Probable results, which may be sequenced from specific initiating events, are analyzed, and adequate general countermeasures (safety functions) are selected to ensure safety against risks. To identify the initiating events, various data on underwater tunneling such as empirical analyses; design reports; case studies of practical problems; numerical analyses and model test results; and hydrologic analysis results were used. Event trees corresponding to three significant initiating events were constructed. Each event



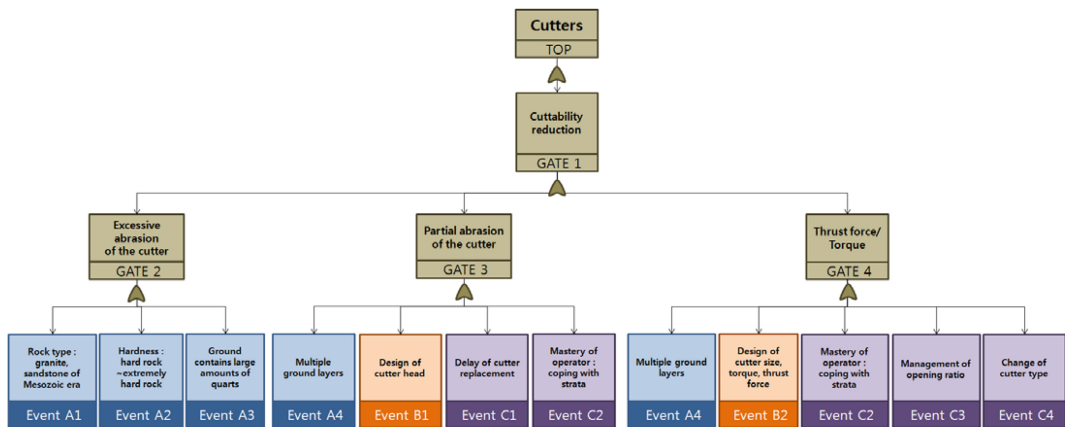


Figure 12. Analysis of risk factors associated with cutter-related malfunction.

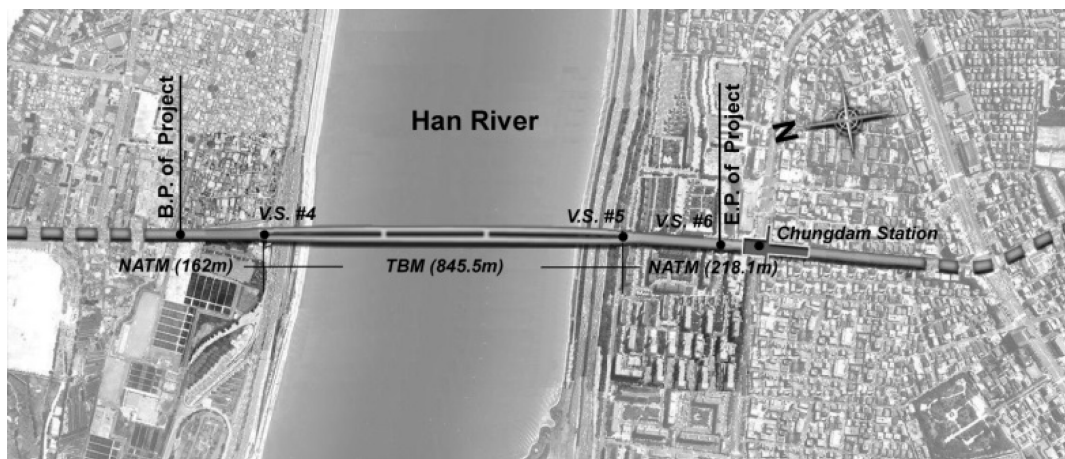


Figure 13. Construction site plan.

tree consists of five countermeasures that construct 32 paths, and the probability of each path is calculated. A quantitative risk assessment was performed and the occurrence probabilities and criticalities of the paths depending on the initiating events were considered. Based on these ETA results, it was found that the selected underwater tunnel site (see Fig. 13) still has a considerable probability of accidents in spite of common countermeasures. Based on the evaluated risks, improved target probabilities are proposed to reduce the probability of disaster during construction. Additional countermeasures, in other words mitigation actions, corresponding to the new target are considered. As a result, technical risks and economical losses of property can be minimized in a systematic way. It was found that the ETA is an effective method for the evaluation and quantitative analysis of probable risks and for the proposition of countermeasures for hazardous environmental conditions such as the underwater tunnel.

#### 4 CONCLUDING REMARKS

As a keynote speech, the author tried to summarize recent efforts to optimize any geotechnical issues in the analysis and design of underground structures.

The author is currently serving as the director of the Undersea Tunnelling Technology Center funded by Korean Government; main target is to optimize the tunnelling technology even in the subsea tunnels. The author hopes the effort to optimize the tunnelling projects around the world both in technology and in cost savings is going on everywhere.

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