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CONSTRUCTION OF SUBWAY TUNNEL BENEATH EXISTING VEHICLE UNDERPASS

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SUMMARY

For the construction of twin single track subway tunnels by NATM within close proximity of existing vehicle underpass in the highly congested area of downtown Seoul, finite element analyses were performed to evaluate the ground responses during tunnelling and also the stability and safety of the underpass structure and subway tunnels.

Results of the analyses indicated the need to improve the soil beneath the underpass, and pre-grouting was carried out prior to the tunnel excavation. During tunnel construction field measurement program was implemented to confirm the results of anslyses and to control the tunnel construction procedures, thus ensuring stability of the existing structres.

INTRODUCTION

The rapid growth of Seoul Metropolitan area requires provision of speedy, efficient and economical mass transit system to meet the daily transportation needs of growing urban population. Seoul subway lines 1 through 4 totaling 115 km have already been constructed and in operation, and more than 100 km of additional subway lines and extension of existing lines are presently under design or construction.

When establishing extensive subway network in congested CBD area, construction of tunnels in close proximity of existing structures is unavoidable. The twin subway tunnels in front of the National Museum (formerly Capital Building) are not only located in an area highly congested with heavy traffic and high-rise Government Office Building, but also close to a historical palace gate (refer to Fig. 1). More critically, the tunnels had to cross under an existing vehicle underpass structure which is located only 4.3m above the tunnel crown (refer to Fig. 2)

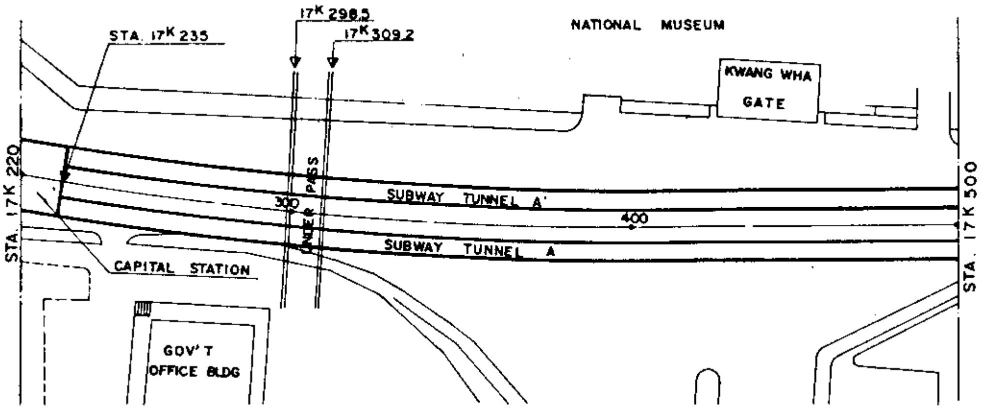


Fig. 1 Site Location

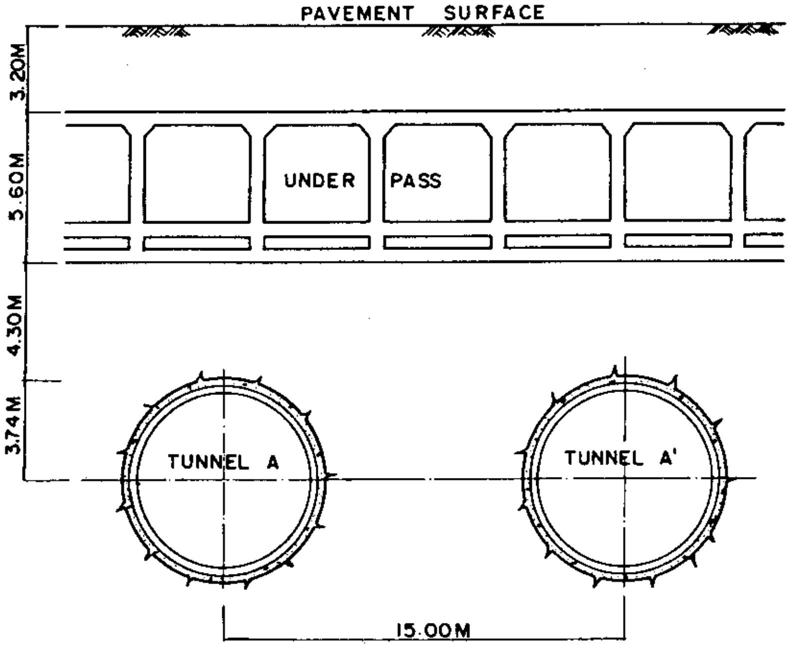


Fig. 2 Sectional View of Underpass and Tunnels

Extensive study was conducted prior to the tunnel construction and the ground behavior during tunnel exavation was evaluated through a series of finite element analyses. Based on the results of analyses, a grouting program to improve the alluvial and residual soil underlying the underpass structure and a staged tunnel excavation plan were established. In addition, field measurement program was implemented during tunnelling to monitor the actual ground behavior and to control the tunnel construction procedure.

This paper describes the approaches and techniques used for finite element analyses, and the subsequent tunnel construction plan. Results from the analyses and field measurements are compared, and reliability of the analyses is assessed.

SUBSURFACE CONDITIONS

General setting of the geology in Seoul Metropolitan area is dominantly Precambrian gneisses and schists, intruded by Jurassic granite. Overtopping these bedrocks are alluvial soils of widely varying thickness and properties. The granite and regional metamorphic Precambrian rocks have also been subjected to different degrees of weathering at different locations. The weathering is generally deep, and resulted in very thick residual soil layers particularly in the valley areas. The weathering profile is also very complicated due to complex discontinuities existed in the bedrock.

The geological formation at the tunnelling site is in line with the general setting of regional geology. However, the site is covered with relatively thick alluvial materials, since it is located at the foot of Bukhan mountain between old valleys.

The alluvial soil generally consists of very silty medium to coarse sand with some silty clay. The underlying residual soil layer is typical of completely weathered granite, which is characterized by loss of original rock texture and strength reduction upon disturbance combined with wetting. The weathered rock easily turns into silty sand and rock fragments when excavated or crushed, and the underlying soft rock layer is highly to moderately weathered granite. The groundwater table is relatively high and groundwater inflow was expected during tunnelling.

FINITE ELEMENT ANALYSES

Finite Element Model

The finite element analysis program used in this study is a two dimensional nonlinear program, which was developed particularly for the purpose of analyzing ground behavior during tunnelling under various loading conditions. In the program. material behavior is idealized as elastic and perfectly plastic, and different yielding criteria such as Mohr-Coulomb's, von Mises', and Drucker-Prager's can be selected depending upon the materials to be represented. It is also assumed materials when subjected to tension beyond the allowable tensile strength undergo cracking. Subsoil layers and tunnel structure including shotcrete layer are represented by isoparametric plane strain elements, and truss elements are used for rock bolts.

Fig. 3 shows the finite element model used in simulating the tunnel construction. Also shown is the subsurface profile at the site.

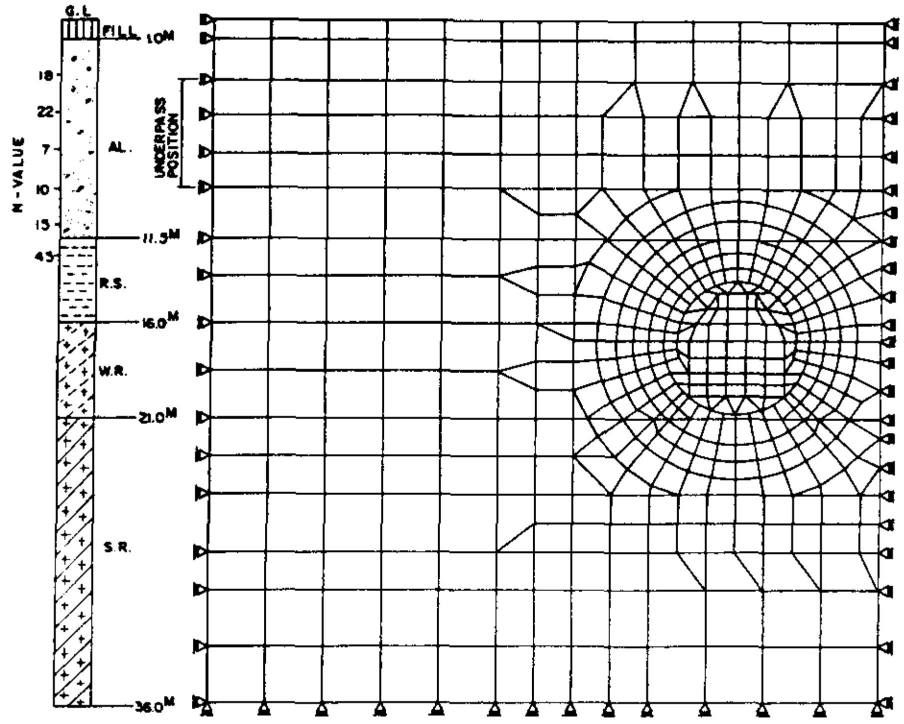
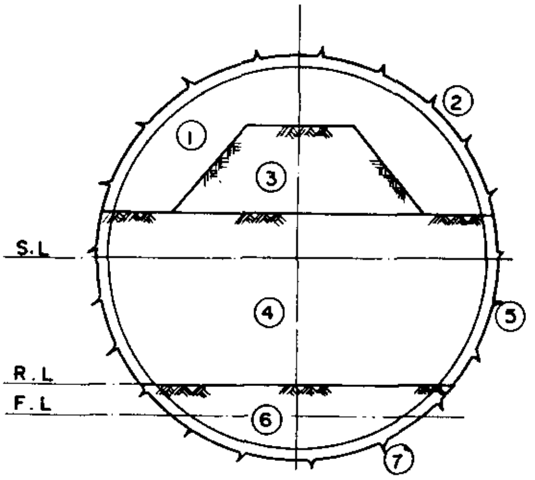


Fig. 3 Finite Element Model Used

Initial Analysis

Ring-cut and short bench type excavation with shotcreting was adopted for tunnel construction, and this was simulated by a total of 7 construction steps as shown in Fig. 4.



Excavation & Shotcrete Steps

1. Ring Cut
2. Upper Half Shotcreting
3. Core Excavation
4. Lower Half Excavation
5. Lower Half Shotcreting
6. Invert Excavation
7. Invert Shotcreting

Fig. 4 Tunnel Excavation Steps for Numerical Simulation

The results of intial analysis indicated that the Government Office Building and the palace gate would not be adversely affected, since less than 5 mm of ground settlement was expected at a distance of 20 m from the tunnel centerline. Directly above the tunnel excavation, however, the maximum ground settlements of 54 mm and 37 mm were predicted at the base of underpass structure and at the ground surface, respectively. These settlements would occur mostly within 10m of the tunnel centerline which produces unacceptably high bending stress in the underpass structure. Furthermore, the analysis indicated possible development of plastic zone in the tunnel crown area.

Final Analysis

Due to the unfavorable results of initial analysis, improving the alluvial and residual soil underlying the underpass structure by grouting was considered. The analysis was carried out again using the same finite element model but with improved strength characteristics of grouted soil.

The results of analysis indicated significant reduction in estimated settlements. As shown in Fig. 5 the predicted settlements at the base of underpass and at the ground surface were reduced by more than half.

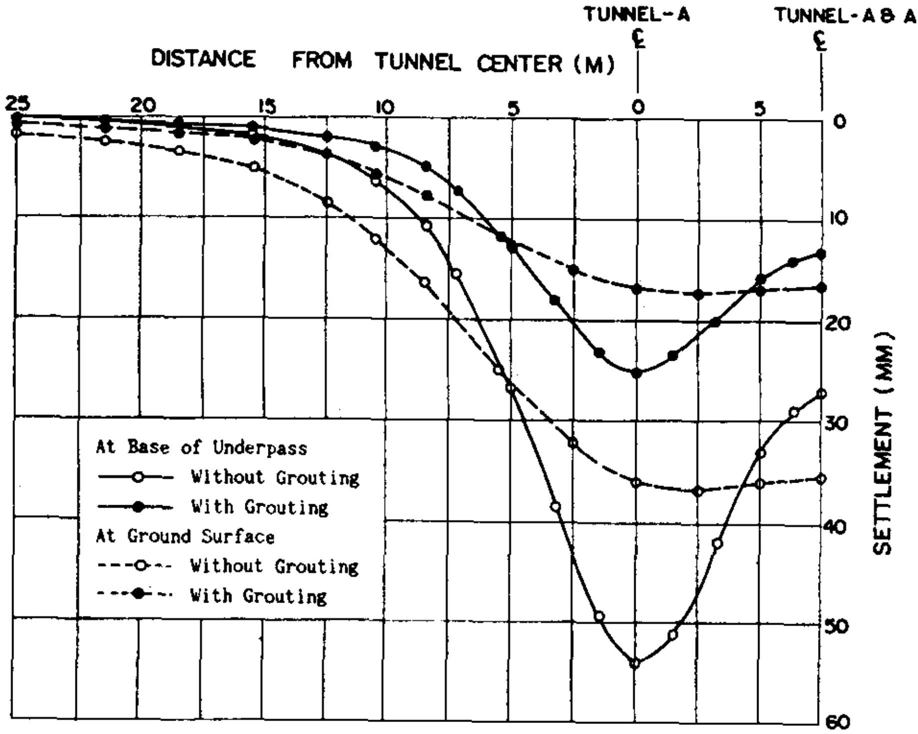


Fig. 5 Predicted Settlements with and without Grouting

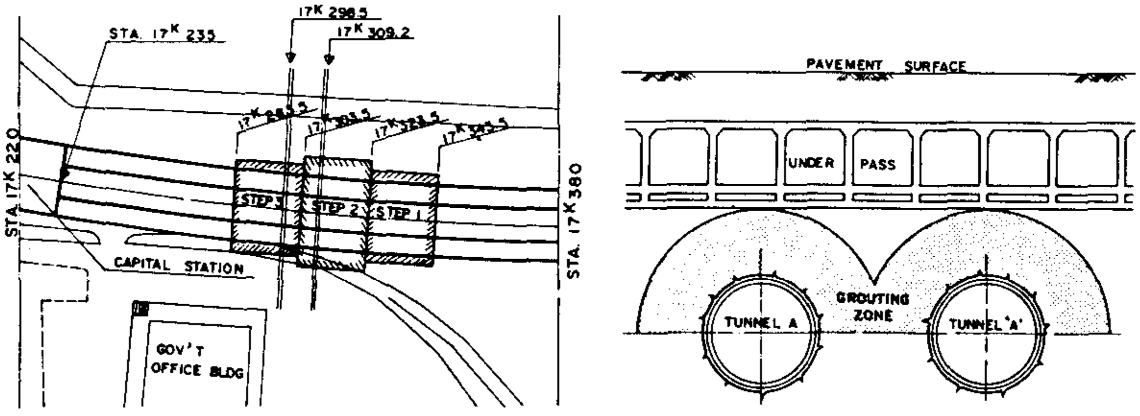
It was reported that during excavation for the underpass construction a large amount of groundwater inflow was experienced, and double base slabs were constructed to provide a drainage chamber. Due to its relative rigidity the underpass structure was evaluated to be capable of withstanding the reduced settlement predicted by the finite element analysis. The analysis also indicated that the plastic zone at the tunnel crown would not develop when the soil was grouted.

Based on the results of these analyses, it was decided to grout the alluvial and residual soil layers below the underpass structure prior to the tunnel excavation. The grouting program provided additional benefit of controlling groundwater inflow during tunnel excavation, thus increasing the stability of tunnel face.

CONSTRUCTION CONTROL AND MONITORING

Grouting Program and Field Instrumentation

Although it was desirable to carry out the grouting operation inside the underpass structure so as not to interrupt the tunnel construction, it was not passible to block the traffic in the underpass. Therefore, the grouting operation had to be executed from the tunnel face in three steps as shown in Fig. 6.



Plan View

Sectional View

Fig. 6 Grouting Plan

The step 1 grouting was carried out at a distance of approximately 40 m from the underpass location. Since the step 1 grouting area is at a sufficient distance from the underpass structure, chemical grouting was used primarily for the purpose of controlling groundwater inflow. No strength improvement was expected from the chemical grouting. For step 2 and 3 grouting areas, however, microcement based grouting was adopted to improve the strength characteristics of the soil layers which contained a fair amount of silt size particles.

In order to monitor the ground behavior during grouting operations and subsequent tunnel excavation, convergence pins were installed inside the tunnel and ground surface settlement points were established at 10m intervals. Tunnel crown settlements were also measured at every 10 m and an inclinometer was installed on the walkway near the Government Office Building. Fig. 7 shows the types and locations of instruments installed.

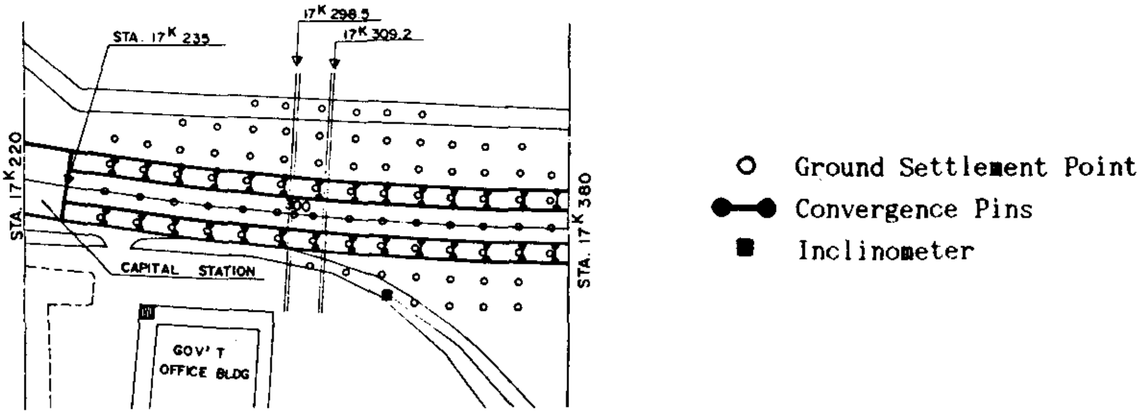


Fig. 7 Layout of Instruments Installed

Comparison of Predicted and Measured Responses

In Step 1 grouting area where chemical grouting was used and the ground behavior can be compared with the results of initial analysis without strength improvement in soil layers, measured ground settlements ranged from 41 to 98 mm which were in excess of predicted maximum settlement of 37 mm from the initial analysis. It was judged that this phenomenon was due to approximately 3 weeks period during which tunnelling operation was stopped to allow grouting from inside the tunnel and also the delay in invert closure with shotcreting. Consequently, for tunnelling in Step 2 and 3 grouting areas, it was decided to install forepoling to improve the stability of tunnel crown area and special attention was paid to apply the invert shotcreting immediately following invert excavation.

Fig. 8 and 9 show the examples of field measurements compared with the predictions in the underpass area.

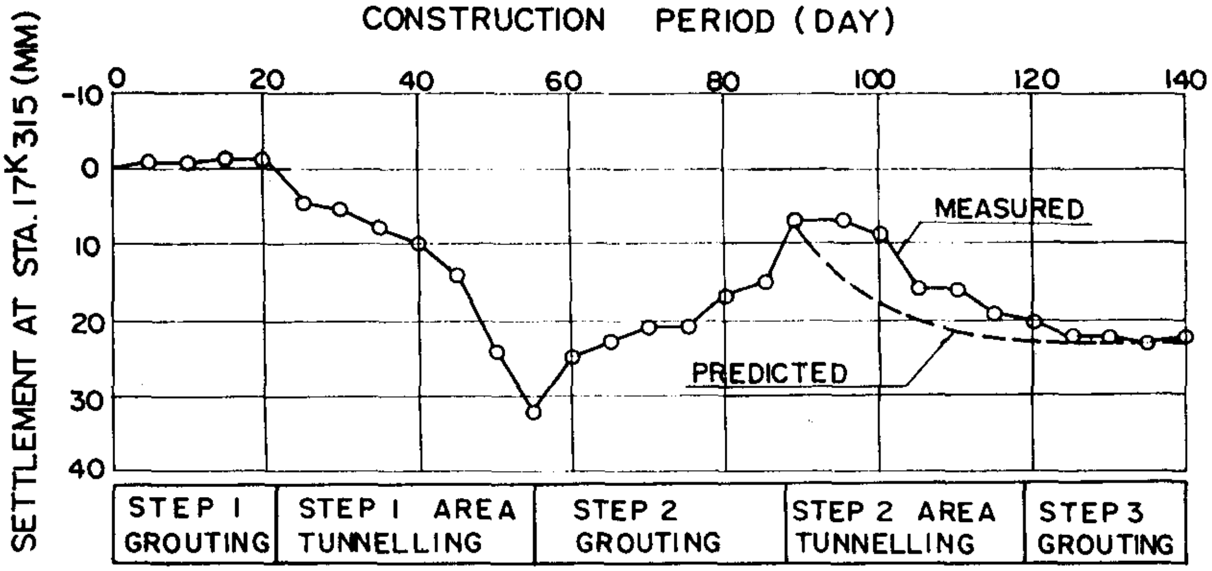


Fig. 8 Comparison of Predicted and Measured Ground Surface Settlements

The measured ground settlements clearly show the effect of grouting operation. Therefore, an extreme care was exercized in controlling the grouting pressure to maximize the soil improvement and at the same time to control the ground settlement. The ground settlement measurements show that the final settlement compares reasonably well with the predicted settlement value, although the ground heave from grouting operation was not reflected in the numerical simulation. The underpass structure was continuously observed throughout the tunnel construction period, and did not show any noticeable signs of distress.

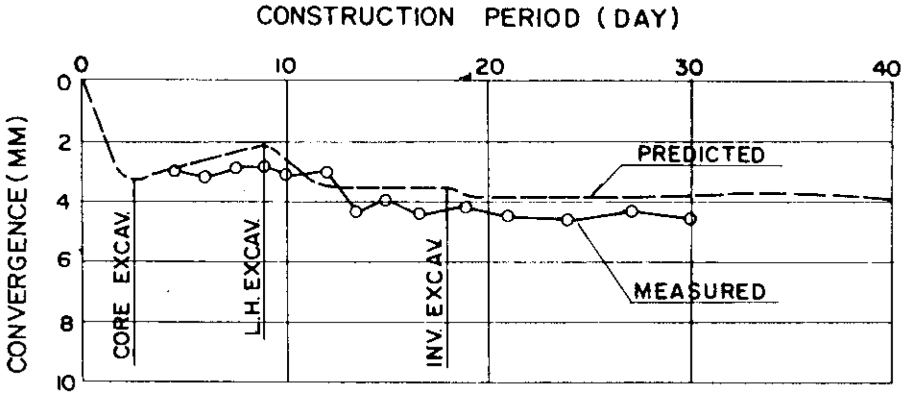


Fig. 9 Comparison of Predicted and Measured Tunnel Convergence

The measured tunnel convergence agreed well with the predicted values and the tunnels were safely completed without any notable incidents. The inclinometer readings did not show any lateral ground movements confirming the results of analysis which showed no significant ground movement beyond 20 m of tunnel excavation.

CONCLUSION

The twin subway tunnels crossing under an existing vehicle underpass within close proximity were successfully constructed without causing any adverse effects on the adjacent structures. It was possible to complete the subway tunnels successfully by properly defining the potential problems in advance through refined analyses and taking remedial measures prior to the construction.

In addition, field instrumentation and measurement results were fully utilized to strictly control the tunnel construction procedures, to assess the safety of tunnels and adjacent structures, and to take additional measures during construction for successful completion.

The project described in this paper proves that subway tunnels in a congested urban environment can be safely constructed through proper analytical methods combined with field instrumentation and monitoring.

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