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# Ground movements associated with subway tunneling in Korea

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SYNOPSIS: Described in this paper are the magnitude and the distribution of ground movements and the factors affecting ground settlements caused by NATM (New Austrian Tunneling Method) tunneling. The ground movement data obtained from the field instrumentation are analyzed to suggest the measures to reduce the NATM tunneling - related ground movements.

## 1 INTRODUCTION

Ground movements associated with urban tunneling in soft ground may cause harmful effects on nearby utilities and structures by disrupting their normal functions. Therefore it is important to identify the sources of ground movements and to estimate the magnitude and the extent of ground movements prior to tunneling.

As of 1992, Korea has 160 km - long subways in two cities, but the total length will be expanded to 738 km by the year 2008 in four major cities. Tunneling is being done mostly by the New Austrian Tunneling Method.

The paper presents case records on ground movements associated with subway construction in Seoul and Pusan. The magnitude and distribution of ground movements are compared with other findings such as results of physical model tests and case records of other countries.

The factors affecting magnitude and extent of ground settlements associated with the NATM tunneling are considered and finally measures to reduce the NATM tunneling - related ground movements are suggested.

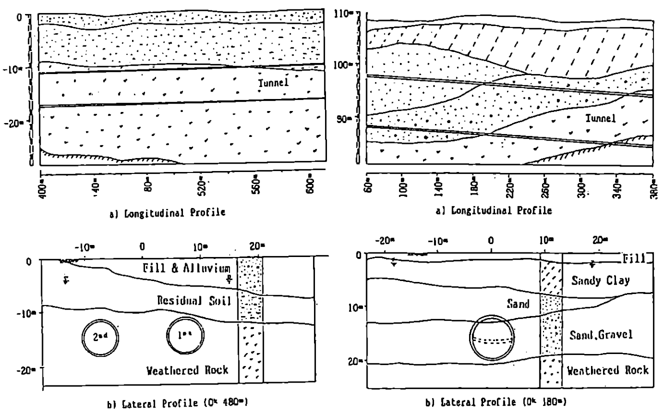
## 2 DESCRIPTION OF WORKS AND GROUND CONDITONS

### 2.1 Seoul Subway 3rd and 4th Lines

Seoul Subway 3rd and 4th Lines with NATM tunneling consisted of a 10 Km long 7.5 m diameter twin tunnel with a depth of burial ranging from 12 m to 20 m. The pillar width between two tunnels varied from 5 m to 15 m. Excavation was carried out in two parts-the upper and low part-termed the short bench-cut method.

The length of the short bench was about 5 m. The tunnel was mostly driven through the weathered granitic rocks, residual soils and alluvial soils overlying it. Some sectors of the subway was driven mainly through soft residual soils with weathered rocks in the invert. The predominant feature of the residual soils were high permeability and high deformability. Therefore the chemical grouts containing water-glass($MNa_2O$. $NSiO_2$) were injected from the tunnel face after excavation of upper half to cut off the ground water intrusion and to improve the soft ground. The stabilized zone around upper half was 2.5 m thick and arched.

The typical geological profiles of Seoul Subway 3rd Line Sector 320 with soft ground tunneling are shown in Fig. 1-1. The ground consists of four different kinds of materials of which engineering properties are shown in Table 1. The valuse of Cu and $\phi$ were obtained from triaxial U tests and the value of $K_v$ by variable head borehole tests.




1) Seoul Subway, Sector 320 2) Pusan Subway, Sector 210
Figure 1. Geological Profiles

Table 1. Summary of Engineering Properties of Ground (Seoul Subway, Sector 320)

| | Fill | Alluvial Soil | Residual Soil | Weathered Rock |
|---|---|---|---|---|
| Water content(%) | | 28-40 | 17.0-21.5(19.4) | 9.9-22.7 (17.6) |
| Total unit weight(g/cm³) | 1.6 | 1.6 | 1.8-2.0 (1.9) | 1.9-2.1 (2.0) |
| Young's modulus, $E_s$ (kg/cm²) | 150 | 150 | 76-651 (200.1) | 2737-18611 (8749) |
| Cohesion, $C_u$(kg/cm²) | 0.1 | 0.08-0.09 (0.085) | 0.0-0.36 (0.08) | 10-40 (26.) |
| Friction angle, $\phi$(°) | 20 | 24-34 (29) | 20-38 (31.6) | 43-57 (49) |
| Poisson's ratio, $\nu$ | 0.35 | 0.35 | 0.33 | 0.31 |
| Permeability coefficient, $K_v$(cm/sec) | - | - | $6.4\text{-}5.4\times10^{-3}$ | - |

( ) : Average Value

2.2 Pusan Subway 1st Line

Pusan Subway 1st Line with NATM tunneling consisted of a 5.3 km long, 10 m diameter single tunnel with a burial depth of 9 m to 18 m. Excavation was carried out in two parts-the upper and low part-termed the short bench-cut method like the Seoul Subway. However the soft ground tunneling in Pusan Subway was carried out by the ring-cut method with the temporary invert lining.

The typical subway sector with soft ground tunneling was station No.210. The tunnel of sector 210 was driven through the weathered rock and sand with gravel and sandy clay overlying them. The thickness of sandy clay was about 2 m to 8 m. It's predominant features were low permeability and low N value(see Table 2). The chemical grouts were injected from tunnel face after excavation of upper half like Seoul Subway.

The typical geological profiles of Sector 210 are shown in Fig. 1-2. The ground consists of 4 different kinds of soils of which the engineering properties are shown in Table 2.

Table 2. Summary of Engineering Properties of Soils (Pusan Subway Sector 210)

| | Fill | Sandy clay with gravel | Sand, Gravel | Silty sand |
|---|---|---|---|---|
| Total Unit Weight $\gamma_t$ ( g/cm³) | 1.8 | 1.7 ~ 1.9 (1.8) | 1.8 ~ 2.0 (1.9) | 1.8~ 2.0 (1.9) |
| SPT N-value | 3~12 (6) | 5 ~ 23 (14) | 4 ~ 38 (23) | 6 ~ 32 (20) |
| Cohesion, $C_u$ (kg/cm²) | - | 0.6 ~ 2.5 (1.0) | 0.0 ~ 0.4 (0.1) | 0.05 ~ 0.8 (0.3) |
| Friction Angle, $\phi$ | - | 11 ~ 23° ( 18° ) | 23 ~ 35° ( 28° ) | 18 ~ 33° ( 24° ) |
| Poisson's Ratio, $\nu$ | 0.3 | 0.3 | 0.35 | 0.35 |
| Permeability coefficient, $K_v$(cm/sec) | - | $6\times10^{-4}$~$4\times10^{-5}$ | - | - |

## 3 FIELD INSTRUMENTATION

Two types of instrumentation programs, the so-called A type and B type were applied in Seoul and Pusan subway projects. The instrumentation program of A type is to measure daily ground surface settlements and lining deflection for routine construction management. The lines of measurement points were arranged at intervals of about 15m. The instrumentation program of B type involved monitoring variables such as surface and subsurface displacements, lining deflections, axial stress in rockbolts, and shotcrete liner stress which were useful for evaluating the design and the construction procedure of the project. The instrumentation program of B type was selected at sections of the project that had conditions typical of the whole project.

## 4 GROUND MOVEMENT-RESULTS AND DISCUSSION

### 4.1 Ground Movement Profile

GROUND SETTLEMENT : A considerable amount of field measurements, numerical analyses, and model studies have been reported recently on the ground movements associated with tunneling. It is well established that the transverse and the longitudinal profiles of surface settlement trough can be described by Gaussian normal probability curve and the error function, respectively.

Peck suggested the relation between width of settlement trough and depth of burial from assembling settlement data (Peck, 1969). Fig. 2 shows the observed data available from two cases of Seoul and Pusan Subways plotted in Peck's plot. The results agree in general to Peck's plot. However, the data from Pusan Subway with single tunnel are plotted in the zones with better ground conditions than the data from Seoul Subway with twin tunnels.

Shown in Fig. 3 are typical longitudinal profiles of surface settlements and subsurface settlements along the tunnel axis for Pusan subway tunnels. It is seen that the combination of two or more error functions can reasonably represent the observed longitudinal settlements depending upon construction sequence, that is, the number of excavation stages. Ground heaving is observed from Pusan Subway 1st Line Sector 210 with chemical grouting. Amount of heave at surface is about 2 mm and at 8m below ground surface is about 4 mm. It is seen in the figure that for given ground condition, the subsurface settlements are larger than the surface settlements.

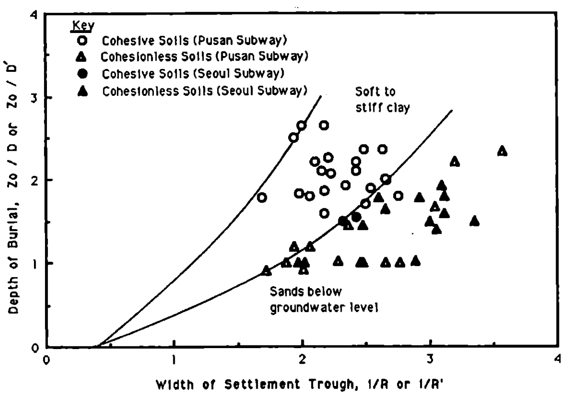



Figure 2. Width of Settlement Trough versus Depth of Burial

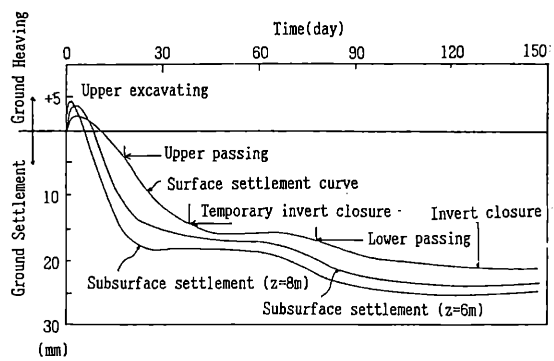



Figure 3. Observed Logitudinal Surface Settlement

LATERAL DISPLACEMENT : In mining subsidence, horizontal displacements are traditionally related to settlements under either of two assumptions: the horizontal displacement at a point is proportional to the slope of the settlement trough or the horizontal displacement at a point corresponds to the ground movements that are directed toward the center of the excavation.

For a settlement trough following the shape of a normal probability curve both of the two assumptions lead to the same distribution function for lateral displacements.

$$S_h/S_{hmax} = 1.65x/i \cdot \exp(-x^2/2i^2) \quad \cdots\cdots (1)$$

The equation predicts that the lateral displacement is zero when x=0 and the maximum when x=i. The lateral displacement is about 18 percent and 5 percent of the maximum lateral displacement when x=2.5i and x=3i, respectively.(peck, 1969)

Equation 1 is fitted with the lateral displacements observed from a test section in Pusan Subway in Fig 4. The values of x/i at which the lateral displacement maximizes with excavation stages appear to be slightly smaller than unity. However, the displacements at lateral distance of 2i and 3i away from the tunnel centerline are grossly underestimated by equation 1.

The ratio of $S_{hmax}/S_{smax}$ for upper excavation is 0.54 and the ratio of $S_{hmax}/S_{smax}$ for lower excavation is 0.40. The ratio in the European coal fields ranges between 0.16 and 0.45 with an average of 0.3. The ratio in Hong's model test ranges between 0.05 and 0.55 with an average of 0.3. The ratio in the test section of Pusan Subway is seen to be somewhat larger than their average of 0.3. The reason may be considered as following : the magnitude of total surface settlement associated with tunneling was small as the lower half was excavated under the upper half supported by shotcrete lining and grouting.

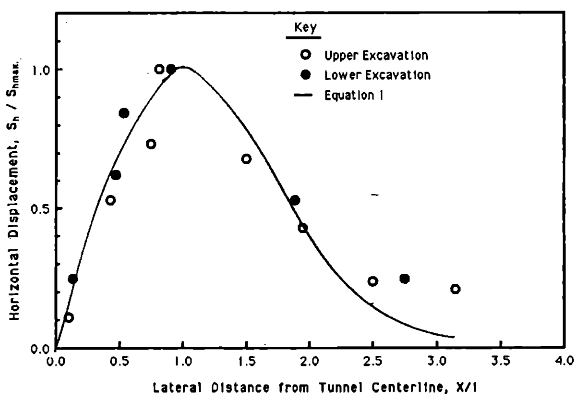



Figure 4. Distribution of Horizontal Displacements at Surface

4.2 Factors Affecting Ground Settlements

GROUTING : Fig. 5 shows that the observed data available from subway tunnels with/without grouting are plotted in Peck's plot to understand grouting effect on settlement trough width. It is seen that the field data are generally plotted in the correct zone for each type of soil as shown in the figure. However, the test sections with grouting tend to have somewhat wider settlement trough than those without grouting. In the former, the width of settlement trough was 30 percent wider than the latter.

This indicates that ground improvements contribute to wider settlement trough while ground loosening contributes to deeper settlement trough.

Shown in Fig. 6 is a relationship between the volume of surface settlement trough and the maximum surface settlement. The slope of the curve is an indication of trough width. The subway tunnels in cohesionless soils show steep slopes of wide trough widths whiles the tunnels in cohesive soils have narrow trough widths. Significant amount of volume decrease is involved as grouting effect. About 40 perecent of the volume of the surface settlement trough was reduced due to the grouting.

Therefore Fig. 5 and Fig. 6 indicate that grouting tends to decrease the magnitude but increase the extent of the surface settlements. It is noted that the surface settlements at some lateral distance away from the tunnel center line were somewhat larger than those near the tunnel center line during the excavation of lower part. The reason is considered to be due to inflow of large amount of ground water through the lower part of the excavation as grouts are only injected from the tunnel face in the upper half.

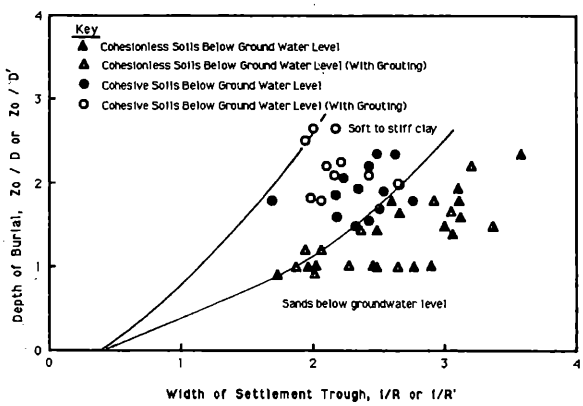



Figure 5. Width of Settlement Trough versus Depth of Burial

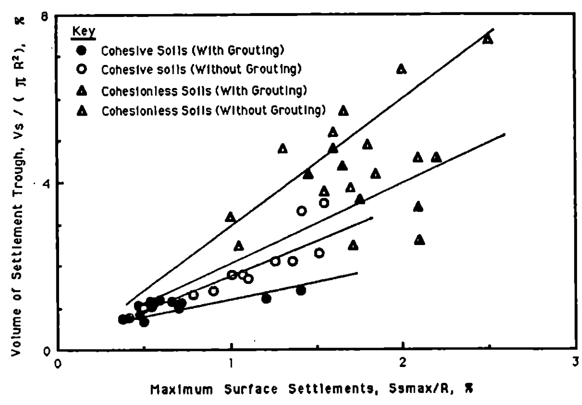



Figure 6. Volume of Settlement Trough versus Maximum Surface Settlement

HALT TUNNELING OPERATION : Development of ground settlements in general stopped when tunneling operation is halted. However time-dependent settlements which continued for several weeks or several months after tunneling operation was halted were observed in Pusan Subway Sector 210. The surface settlements which is defined here as "halt settlement, St", occurred after tunneling operation was halted and the invert was closed. The settlement data were obtained from the test sections which tunneling operation was halted for about 1 month.

Fig. 7 shows that halt settlement is approximately proportional to the thickness of sandy clay strata over tunnel crown. The reason which large amount of halt settlement is occurred may be considered as consolidation of ground and many cracks of shotcrete liner permitted inflow of much water for Pusan tunnels.

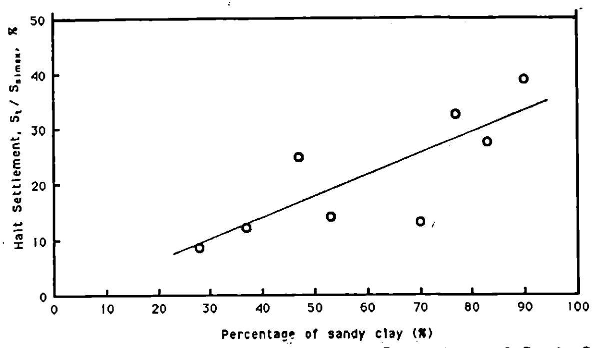



Figure 7. Surface Settlements versus Percentage of Sandy Clay

GROUND CONDITION AND UNSUPPORTED LENGTH OF TUNNEL INVERT : Fig.8 shows a relationship between maximum surface settlement and longitudinal unsupported length of invert with stability ratio, Ns, where Ns is the ratio of the overburden pressure, Po and the undrained shear strength, Cu of the ground. The figure indicates that the longer becomes the unsupported length of invert the larger becomes the surface settlement proportionally. The magnitude of surface settlement depends also on the magnitude of the stability ratio. Thus, in softer ground tunneling unsupported length of invert or timing of invert closure becomes more important factor affecting ground settlement.

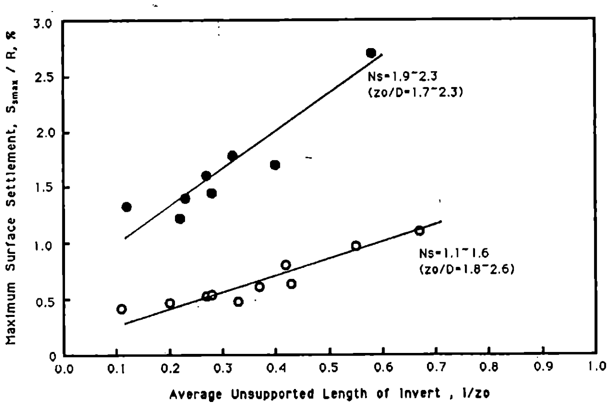



Figure 8. Maximum Settlements versus Average Unsupported Length of Invert

EXCAVATION STAGE : To understand the magnitude and the distribution of surface settlements occurred in each stage of excavation, the settlement data obtained from single tunnels in Pusan Subway are plotted in Fig.9. The ratio of $S_{s2max}/S_{s1max}$ is about 0.37 and the ratio of $i_2/i_1$ is about 1.55, where $S_{s1max}$ ($S_{s2max}$) is the maximum surface settlement occurred during tunneling of upper half (lower half). Therefore, the magnitude of surface settlements was larger during the excavation of the upper half, while the extent of surface settlements were larger during the excavation of the lower half. The reason may be considered as following : for NATM tunnels in Pusan Subway, the lower half was excavated under the upper half supported by shotcrete lining and grouting was carried out only from the upper half but not from the lower half.

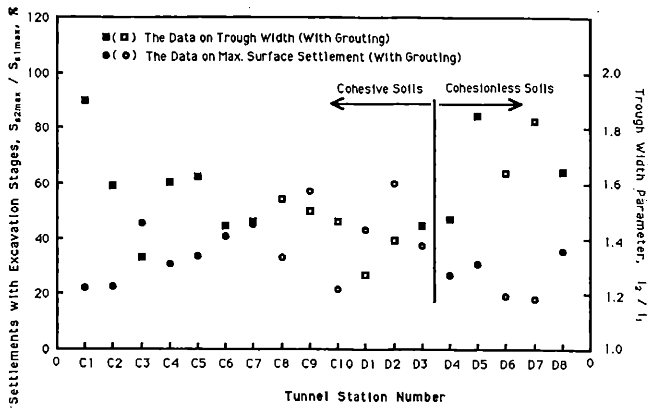



Figure 9. Maximum Surface Settlements and Trough Width with Excavation stages

## 5. CONCLUSIONS

1. In case of NATM tunneling in Seoul and Pusan Subways the lateral distribution of settlements can be approximated reasonably by Gaussian normal probability curve, the longitudinal distribution of settlements by the combination of two or more error functions, and the distribution of lateral displacements by the equation ($S_h/S_{hmax} = 1.65\ x/i \cdot \exp(-x^2/2i^2)$) deformed the normal probability curve.
2. Grouting is a factor decreasing maximum surface settlement but increasing settlement trough width when chemical grouting is only carried out from tunnel upper half like NATM tunneling in Seoul and Pusan Subways. And significant amount of volume decrease (average 40 percent) of surface settlement trough could be realized with proper grouting technique.
3. The longer becomes the unsupported length of tunnel invert, the larger becomes the surface settlements proportionally and the magnitude of surface settlements depends on the magnitude of the stability ratio.
4. Significant amount of surface settlement (over 70 percent of total settlement) is mostly developed at the excavation stage of upper half, and the increment of settlement is approximately proportional to the time-dependent settlement of clay strata over tunnel crown.

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