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Prediction of final displacement of tunnel section during excavation

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ABSTRACT: Certain points on tunnel section start to displace before measurements begin. Therefore prediction of final displacement tunnel section during excavation should be consist of these unmeasured and measured displacements. This paper is focused on methods to estimate the unmeasured displacements and to predict the total final displacements using measurement data in early stage of excavation. An exponential function and linear function are used to find out unmeasured displacements and final displacements are predicted according to total displacements at a distance of one tunnel diameter from the working face.

1 INTRODUCTION

In tunnel, each point on a cross section begins to displace even before the face reaches the section and continues to displace as the face advances past the section until the excavated tunnel becomes stable. Then the displacements cease to developed any longer. For the safe construction of NATM, the most important procedure is to measure displacement at points, such as crown and spring line, on the predetermined section and to predict the final safe displacements. These final displacements might be estimated by a variety of numerical methods but most of them are not reliable because of the uncertainty of input data. For the prediction of final displacement, therefore, it is more practical and safe to use the displacement measured at the early stage of excavation, preferably within the range of one tunnel diameter. Unfortunately, in many cases, the measurements start after the face has reached some distance past the measuring section, resulting in loss of most important displacements data at the early stage of excavation.

This paper is focused on how to evaluate the displacements developed before measurements start, and then with total displacement consisted of unmeasured and measured ones at the early stage of excavation, it is possible to predict displacements at all stage over the entire tunnelling operation. For this study actual measured data in 4highway tunnels in Korea has been analyzed and compared with displacements obtained from 3 dimensional FEM analysis of those tunnels. As a result of this study, the methods of evaluating the unmeasured displacements at the early stage of excavation and predicting the final safe displacements during excavation are presented.

2 PREVIOUS STUDIES

In tunnelling, the prediction methods of tunnel behavior have been classified into the statistical methods and the methods using approximate functions.

Komi(1981) showed that the displacement at one tunnel diameter of distance from face was proportional to the final displacement analyzed with statistical method in NATM tunnel. After that, on the basis of measured data at rail road tunnel Yoshikawa (1983) showed that maximum velocity of displacement at initial stage of excavation was directly proportional to maximum displacement at final stage on the log scale graph.

Ohokawa(1992) analyzed measured data of Kaut tunnel with statistical method and proved that maximum velocity of displacement was proportional to final one. Liu(1986) analyzed initial displacement with fraction function.

After that, Junich(1987) and Minoru(1988) showed that final displacement had been able to predict by exponential function an the basis of initial displacement.

3 INVESTIGATED SITES

Tunnel displacement data obtained at 51 measuring stations in four highway tunnels under construction had been analyzed. The geologic conditions for the four tunnels were similar. They had been dug within highly weathered gneiss. Table 1 shows dimensions of the four tunnels. The numbers of measuring stations were 20 in Gungun, 10 in Daeduk, 11 in Jinyung, and 10 in Sorae tunnel, respectively.

It is most desirable to start measurements as soon as possible after each round of excavation but on sites their starts were not satisfactory. Average distances between the measuring stations and tunnel working faces(called face distance) were about an half of tunnel diameters.

Table 1. Investigated tunnels

Name of Highway	Tunnel Name	Total length	Dimension
Souhaean Highway	Gungun	(up) = 690 m (down) = 700 m	W =12.80 m H = 8.304 m
Honam Highway	Daeduk	(up) = 408 m (down) = 408 m	W =11.15 m H = 7.26 m
Namhae Highway	Jingyung	(up) = 650 m (down) = 660 m	W =17.04 m H = 9.79 m
Seoul loop Highway	Sorae	(up) = 690 m (down) = 700 m	W = 8.15 m H = 6.00 m

Table 2. Face distances of first measurement

Tunnel name	Number of the investigated point	Average first measurement distance from working face (m)
Gungun	20	4.0
Daeduk	10	7.8
Jingyung	11	3.6
Sorae	10	3.0

4 PREDICTION OF FINAL DISPLACEMENT WITH MEASURED DATA

4.1 *Development of prediction method*

Since the measurement starts after the face passed some distance from the measuring station (x_o), it leaves an unmeasured displacement(Y_o). Therefore predicting the final displacement has to be in terms of total displacement including the unmeasured displacement(Fig 1).

Early prediction of final displacement is preferable, but for better prediction some data are required. Using measurement data collected upto the face distance of 1D is thought to be a good compromise. Therefore the prediction of final displacements consists of two stages. The first stage is to estimate the unmeasured displacement and express the total displacement at face distance of 1D(Y_{1D}), and in the second stage the final total displacement(Y_f) is related to it.

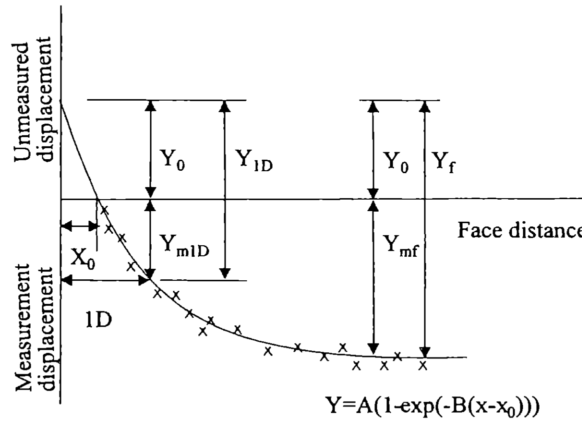


Figure 1. Displacement vs. face distance

4.2 *Estimate of the unmeasured displacement*

If displacements of a point on a tunnel section are plotted against the face distance, it shows a curve similar to an exponential function curve. When all the data had been fitted to an exponential function of the form of Eq.1, the average regression errors were more or less than 10%, which were satisfactory (Table 3).

$$Y = A(1-\exp(-B(x-x_o))) \quad (1)$$

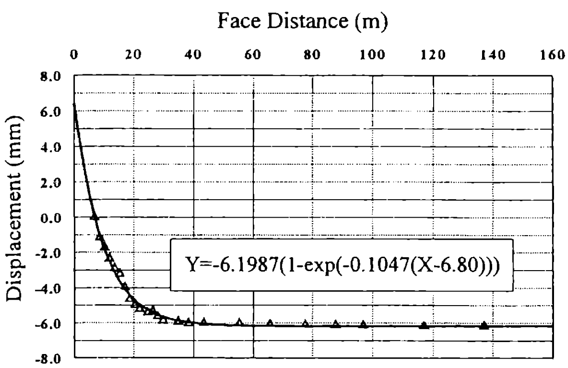
Table 3. Average regression errors

Tunnel name	Site	Measuring point	Average regression error
Gungun	19	57	5.86%
Daeduk	8	24	13.74%
Jinyung	11	35	10.73%

A typical displacement curve is shown on Figure 2. The slope of beginning portion of the curve less than a face distance of 1D is so steep that the measurement data on this portion could be reasonably fitted either by a exponential or a linear function (Fig 3).

4.3 *Relating the displacement at 1D face distance to the final displacement*

With all crown settlement data from four tunnels, unmeasured crown settlements had been estimated by regression with both exponential and linear functions. To them measured settlements at 1D face distance and of final stage were added to give Y_{1D} and Y_f. Then the corresponding two values were plotted as shown on Figure 4 and Figure 5.



Gungun Tunnel 2K+460

Figure 2. Typical regression of displacements by exponential function

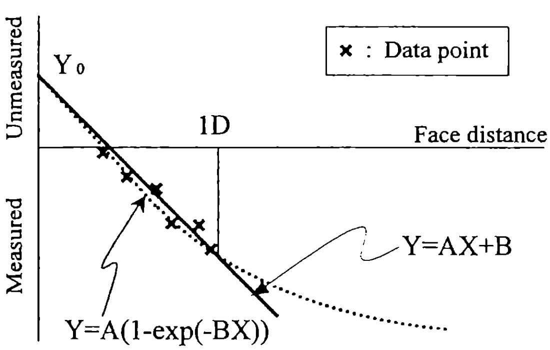


Figure 3. Estimate of unmeasured displacement

The regression equations for both functions are as follows,

$Y_f = 1.42Y_{1D} + 0.79$ for exponential function
$Y_f = 1.45Y_{1D} + 0.96$ for linear function

The coefficient of determination was 0.89 when the unmeasured settlements had been estimated by regression of exponential function and 0.79 for a linear function. Since both equations are similar and R-square values are acceptable, it could be conclud-ed that the unmeasured settlements might be estimated by either a exponential or a linear function and Y_f is about 1.5 times Y_{1D}. But if measurement data are enough for fitting into exponential function, it is preferable for estimate of unmeasured settlem-ents. If data are few, say, less than 5, linear regress-ion is a reasonable choice.

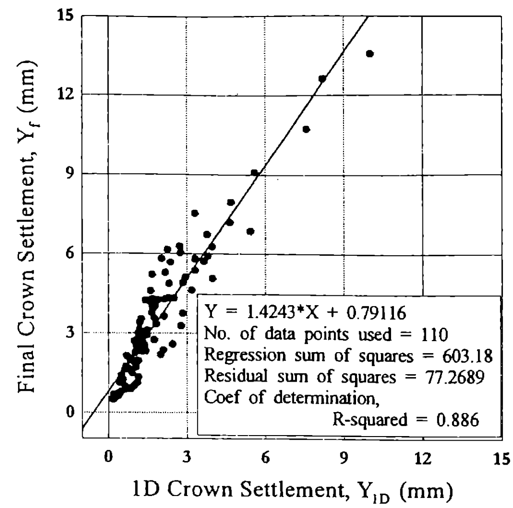


Figure 4. Final vs. 1D total crown settlement with Y_o by exponential function

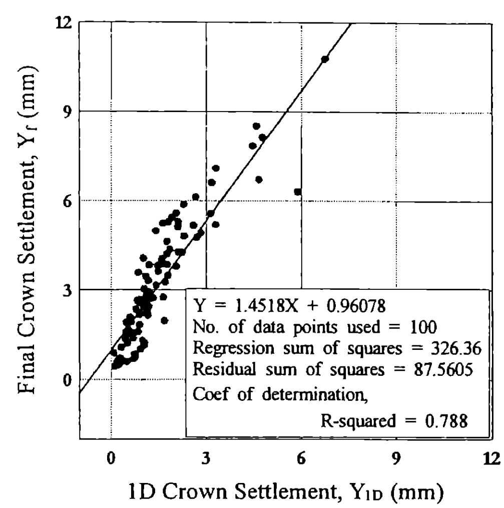


Figure 5. Final vs. 1D total crown settlement with Y_o by linear function

5 STUDY OF TUNNEL DEFORMATION BY NUMERICAL METHOD

5.1 *Method of analysis*

To supplement the results of statistical analysis the deformation of tunnel as excavation work proceed had been studied with numerical method.

With usual two dimensional analysis the develop-ment of tunnel deformation could not be studied effectively as working face advances past a measur-ing station. Therefore three dimensional FEM was used to analyze typical two lane highway tunnels (Figure 6) in several different rock formations(Table 4). In 3D FEM analysis actual excavation processes were simulated as closely as possible with pertinent material properties.

5.2 Results of analysis

Points on a certain measuring station start to displace even before working face reaches it. All displacements developed before and after the working face passed the station had been calculated. Then they were expressed as a fraction of the total displacements and plotted against face distance.
Figure 7 and figure 8 show crown settlements and horizontal convergency, respectively. From the figures it could be seen that more than 60% of total displacement already developed before the working face reached the station (Table 5).

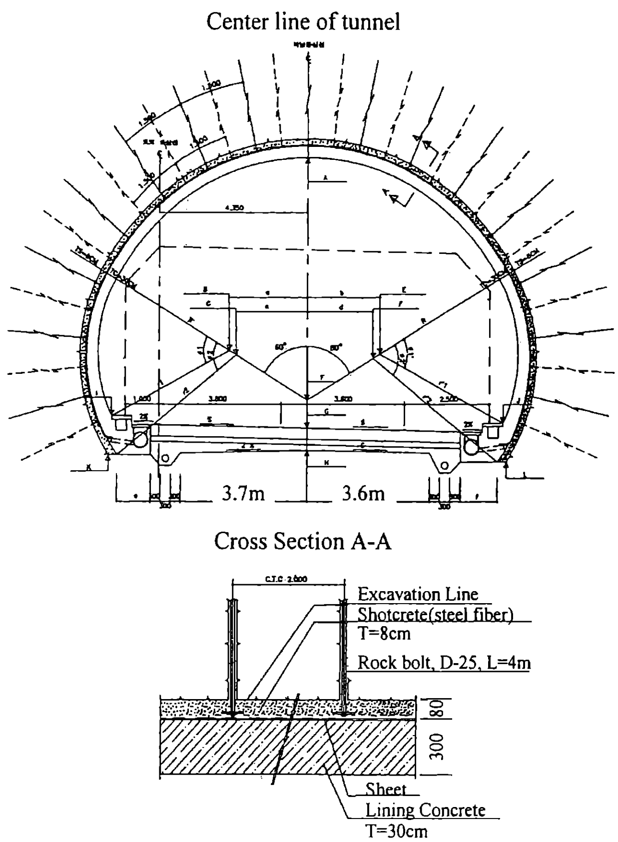


Figure 6. Typical two lane highway tunnel

Table 4. Analyzed tunnels.

Rock type	Excavation method	Face advancing distance per round of excavation
Slightly weathered rock	Full face cut	3.0m
Moderately weathered rock	Full face cut	2.0m
Completely weathered rock,residual soil	Upper and lower half divide cut	1.2m

Table 5. Relative displacements before excavation (Δ_{before})

Rock type	Crown settlements	Horizontal convergence
SW rock	65.63%	68.52%
MW rock	62.5%	63.13%
CW rock, residual soil	60.59%	--------

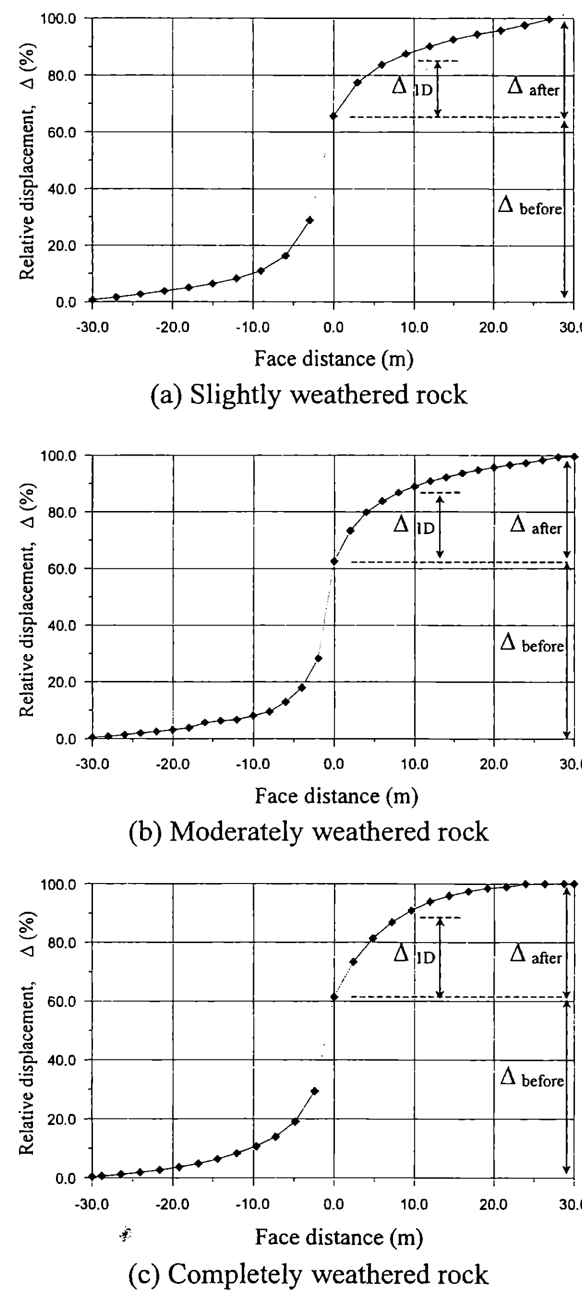
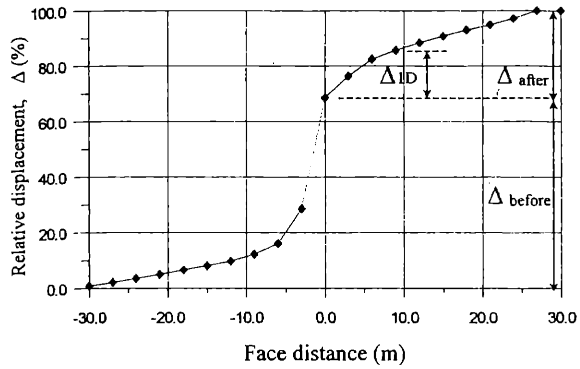
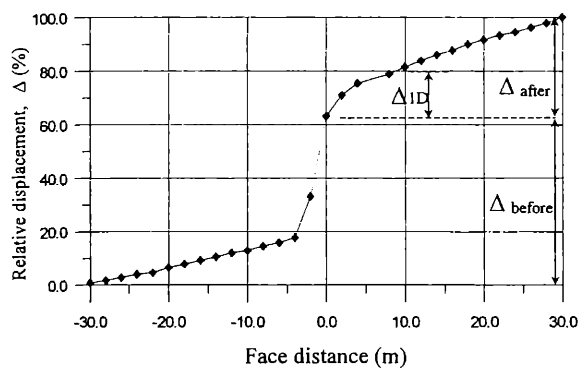


Figure 7. Crown settlement vs. face distance by 3D FEM



(a) Slightly weathered rock



(b) Moderately weathered rock

Figure 8. Horizontal convergence vs. face distance by 3D FEM

5.3 *Comparison by statistical method*

The displacements measured on construction site are only part of displacements developed after excavation, which have been defined as final total displacements previously. To compare the results of numerical analysis with statistical analysis, ratios of displacements at 1D to displacements after excavation were determined. For crown settlements the ratio ranged from 1.43 to 1.55 (Table 6) and for horizontal convergency from 1.88 to 2.43(Table 7).

Table 6. Crown settlements by numerical method

Rock Type	Δ_{after}(%)	Δ_{1D}	Δ_{after}(%)/Δ_{1D}
SW rock	34.4	22.2	1.55
MW rock	37.5	24.3	1.54
CW rock, residual soil	39.4	27.5	1.43

Table 7. Horizontal convergence by numerical method.

Rock Type	Δ_{after}(%)	Δ_{1D}	Δ_{after}(%)/Δ_{1D}
SW rock	31.5	16.8	1.88
MW rock	36.9	15.2	2.43

In most tunnelling sites in weathered rock formation horizontal convergency are very small. Therefore crown settlements are more concerned values for safe construction except in special cases such as tunnelling through soft soil or squeezing rock. In this study only crown settlements are compared. Previous statistical analysis showed that final total crown settlements are about 1.5 times those at 1D face distance. The numerical analysis showed similar results.

6 CONCLUSION

In normal tunnelling operation the measured displacements are more relied upon than analytical calculated displacements to predict the final displacements of tunnel section which are desired for safe excavation. From the results of statistical analysis of measured data obtained in four highway tunnels under construction and study of tunnel deformation during excavation by 3D FEM following conclusions could be drawn.

1. The prediction of final displacemnets should be made in terms of total displacements including the unmeasured displacements which developed before measurements started.
2. The unmeasured displacements could be estimated by regressing measured data obtained in early stage of excavation, preferably before the face advance one tunnel diameter, with either an exponential or a linear function. If the many data points are available within 1D face distance, an exponential function gives better estimate. But a linear function is reasonable choice if the number of data points are fewer than five.
3. The final total crown settlements could be predicted as 1.5 times that of 1D face distance.

REFERENCES

B.H.G. Brady & E.T. Brown, "Rock Mechanic For underground mining", Chapman & Hall, pp.162~193, 1995

Doug Keckler, Tom Bresnahan, Julie A. Hēbert, "GRAPHER™ for Windows", Golden Software, Inc.

E. Hoek & E.T. Brown, "Underground Excavation in Rock", Institution of Mining & Metallurgy, pp.244～328, 1980

Elwyn H. King, "Rock Tunnels", Tunnel Engineering Handbook, CHAPMAN & HALL . CH.7

Junichi S., Masayuki O., Hiroyuki I. & Toshihiko M., "Adaptibility of convergence Forcasting Method for Controlling Tunnel Construction. *2nd International Symposium on Field Measurements in Geomechanics", Sakurai (ed.), Kobe*, pp.907～916, 1987

Kaser P.K., "Effect of stress-history on the deformation behaviorof underground open ings", *13th Canadian Rock Mechanics Symp.*, CIMM, Montreal, pp.133～140, 1980

Liu H. & Wang Z., "Monitoring Analysis of Stability of Caverns in Weak Rock. *Proc. of the Int. Symp. on LRC"*, Helsinki, pp.1319～1328, 1986

Lombardi G., "Long-term measurements in underground opening and their interpret ation with special consideration to the rheological behaviour of the rock", *Field measurements in rock Mechanics*, Zurich, V.2, pp.839～858, 1979

Minoru D., Yuji T. & Kenichi N., "Realtime Construction Control of Tunnel Excavation (part1). *Proc. of the 18th Symp. on rock mech."*, Japan, pp.26～30, 1988

M. L. Jeremic. "*Ground mechanics in hard rock mining"*, Balkema, pp.415～501

Panet M. & A. Guenot, "Analysis of conver gence behind the face of a tunnel", *Tunneling 82, IMM, Brighton*, pp.197～204, 1982