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A study on the prediction of tunnel crown and surface settlement in tunneling as a function of deformation modulus and overburden

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Abstract: The precise prediction of ground displacement plays an important role in planning and constructing tunnels. In this study, an equation for predicting the surface and crown settlement is suggested by examining the theories of ground movement caused by tunnel excavation. From the 3D numerical modeling, the reinforcement effect of UAM (Umbrella Arch Method) is quantitatively analyzed with respect to deformation modulus and overburden. By using a regression technique for the numerical results, an equation for predicting the settlement is suggested.

1. Introduction

Due to the development of industry and increase of population, the construction of underground structures is increasing in the downtown area. As the most of these underground structures are constructed on the shallow and soft ground, the stability of underground structures and adjacent structures rise an important pending problem.

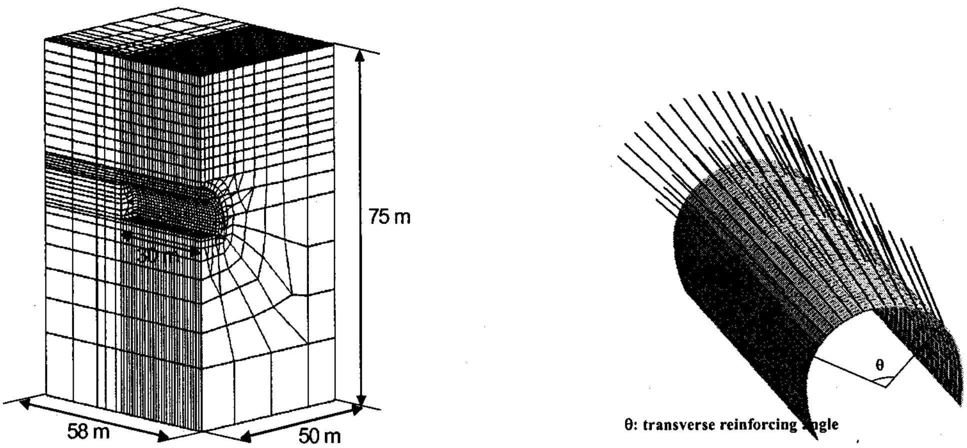
In case that a tunnel is constructed on the poor and soft ground, some kind of auxiliary method of construction are applied to the ground to secure the stability of tunnel. Umbrella Arch Method is commonly applied as an auxiliary method domestically, but the UAM is used in design and construction only based on the empirical experience without any organized thesis and quantitative analysis on the effect of UAM. So in this study, using 3-dimentional Finite Element Method, the reinforcement effect of the UAM is analysed with a mechanical property of ground and overburden thickness as a parameter. And the prediction equation for crown settlement and surface settlement will be suggested through regression analysis.

2. Reinforcement Effect of UAM by Numerical Analysis

2.1 Model and modelling condition

In this study, using the Pentagon3D™ which is the 3-dimentional FEM program, it is modelled construction sequence of mini-bench method and procedure of reinforcement during a tunnel excavation. The tunnel section of model was set to have 10.5m of width, 9.0m of height and about 10.0m of equivalent diameter and the overburden thickness of model was six kinds which were 5, 10, 15, 20, 25, 30m(0.5 ~ 3.0D) from the tunnel crown.

Fig.1 shows the model of the finite element mesh when an overburden thickness is 30m, and the model was set considering a shape of the tunnel section, strata, construction sequence and steel pipe and dividing strata into boundary of upper and lower half. Considering the influence of boundary condition due to the excavation, model of the side part of boundary extend more than five times of tunnel diameter and the lower part of boundary extend more than four times of tunnel diameter. To analyse the reinforcement effect of the UAM, it is arranged the steel pipe (diameter : 60.8mm, thickness : 3.0mm, length : 12.0m) to the 0.4m of distance in transverse direction and 6.0m of distance in a longitudinal direction as a range of angle of 120 degrees from a centre of tunnel. From the opening section of tunnel to the 5 rows, the steel pipe was designed upward as angle of 15 degrees. And to find out the relative reinforcement effect as a ground condition, same range of reinforcement was applied to model with a deformation modulus and overburden thickness.



(a) Solid element (b) Shell and frame element

Fig. 1. The 3-dimentional finite element model.

The boundary condition of upper surface was free and the side and the lower boundary was fixed to vertical displacement. The analysis stage of excavation and reinforcement was set total 35 as ① Apply UAM and excavation → ② soft shotcrete → ③ hard shotcrete → ④ Apply UAM and excavation, and it is considered the construction conditions in the field. The advance was 1.0m and the bench length of the upper and lower half was 4.0m as half times of tunnel height.

In this study, to analyse the characteristics of ground motion and the reinforcement effect, 7 kinds of mechanical property of ground were used as be shown Table 1 and compounding the 7 kind of mechanical properties, 6 kind of different overburden thickness, and appliance of UAM, it is performed 3-dimentional numerical analysis totally 84 kinds of case.

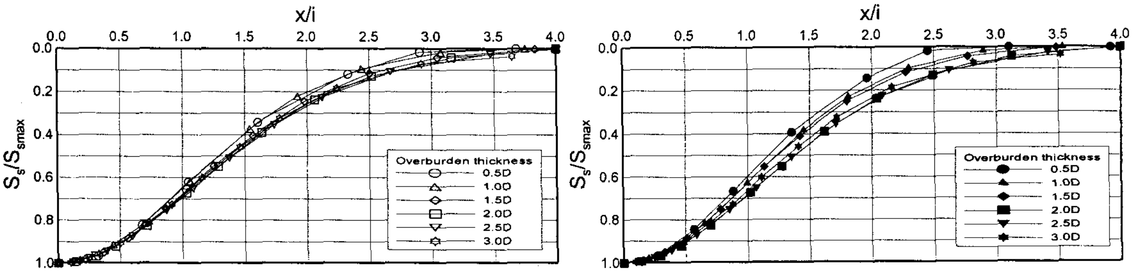
Table 1. Mechanical properties of ground and shotcrete.

Ground type \ Mechanical property		Deformation moduls E (MPa)	Poisson's ratio (v)	Cohesion (MPa)	Friction angle ø (degree)	Unit weight (103 kg/m^3)
Weathered soil	A	20	0.30	0.015	30	1.9
	B	50	0.30	0.03	30	2.0
Weathered rock	C	100	0.28	0.05	32	2.1
	D	300	0.27	0.07	33	2.2
	E	500	0.27	0.1	33	2.2
Soft rock	F	1,000	0.26	0.2	34	2.4
	G	3,000	0.25	0.3	35	2.5
Shotcrete		10,000	0.20	-	-	2.5

Assuming the ground where the steel pipe and the grouting material were inserted as a complex material, the equivalent material property of complex material was applied by the transverse deformation modulus deduced from the 'strain energy theory'. As the volume fraction of grout is increasing, the equivalent material of grouted ground is also increasing. When the volume fraction of grout is between 0.4 and 0.5, grouted grounds indicate that the two times of deformation modulus to the original ground. Refer to the mean grouting rate (20 ~50%) and the existing research, the deformation modulus of grouted ground was applied as two times of deformation modulus of the original ground.

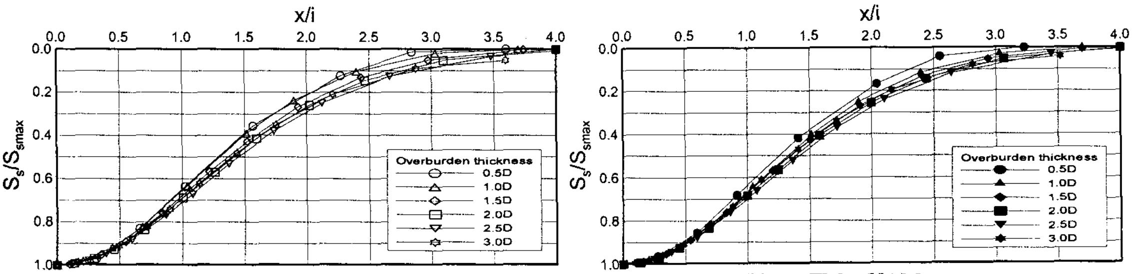
2.3 Result of numerical analysis for surface settlement

As a variation of the deformation modulus of ground and overburden thickness, it is analysed the surface settlement of transversal direction at the top of tunnel. Fig. 2 to 4 shows the variation of surface settlement ratio with normalized transverse distance in ground A.C.F. In case of ground A in which the deformation modulus of ground was 20Mpa, as being shown Fig. 2, the surface settlement ratio was about 61 ~ 70% at the inflection point and about 8 ~ 12% at the point of 2.5i in case that the UAM was not applied. It showed that the more overburden thickness increased, the more ground surface settlement also increased. In case that the UAM was applied, the surface settlement ratio was decreased little by little, as the overburden thickness was becoming smaller the surface settlement ratio was decreased relatively a lot. Ground C and ground F as being shown Fig, 3, Fig, 4, they were showed similar tendency like Ground A, and generally, in case that the overburden thickness is small, the slope of surface settlement curve increased at the inflection point.



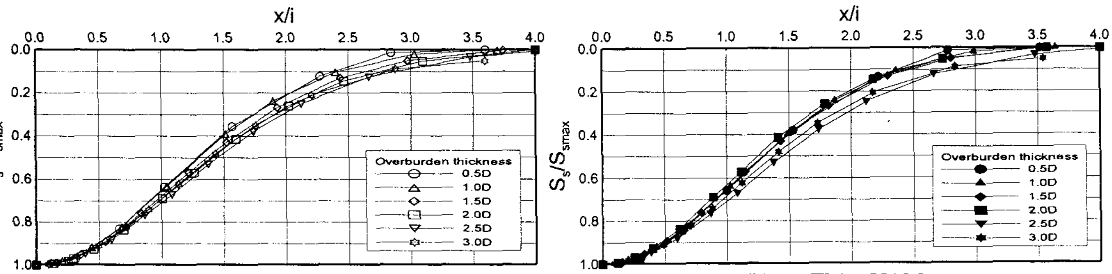
(a) NATM (b) NATM + UAM

Fig. 2. Variation of surface settlement ratio with normalized transverse distance in ground A.



(a) NATM (b) NATM + UAM

Fig. 3. Variation of surface settlement ratio with normalized transverse distance in ground C.



(a) NATM (b) NATM + UAM

Fig. 4. Variation of surface settlement ratio with normalized transverse distance in ground F.

Table 2 and Table 3 present the maximum surface settlement at the tunnel centre as whether the UAM is applied or not, and in Ground A, in case that the UAM was not applied, the maximum surface settlement was 22.6mm at the overburden thickness of 0.5D and the 32.6mm at the overburden thickness of 3D. In case that the UAM is applied, the maximum surface settlement was 16.3mm at the overburden thickness of 0.5D and the 29.4mm at the overburden thickness of 3D, which is the decrease of about 10 ~ 28% comparing to former case. As a result, the smaller of the deformation modulus of ground and the more increase of the overburden thickness, the more increase of surface settlement. Also, as a deformation modulus of ground and overburden thickness are small the restraint effect of surface settlement is relatively good in case that the UAM was applied, so if the UAM was applied to a shallow and soft ground the reinforcement effect is relatively good.

Table 2. Maximum surface settlement (NATM). Unit: mm

Ground type \ Overburden	0.5D	1.0D	1.5D	2.0D	2.5D	3.0D
A	22.6	27.3	32.7	33.1	33.1	32.6
B	9.4	14.0	14.6	15.1	16.1	15.9
C	6.72	8.02	8.62	8.78	8.90	8.31
D	2.83	3.40	3.57	3.63	3.64	3.63
E	1.85	2.18	2.26	2.30	2.31	2.31
F	1.23	1.34	1.35	1.34	1.33	1.31
G	0.46	0.49	0.50	0.50	0.50	0.49

D: Tunnel diameter

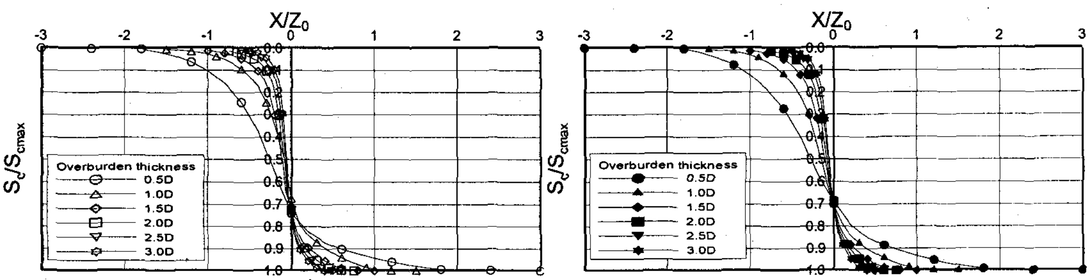
Table 3. Maximum surface settlement (NATM+UAM). Unit: mm

Ground type \ Overburden	0.5D	1.0D	1.5D	2.0D	2.5D	3.0D
A	16.3	25.6	28.4	29.7	30.0	29.4
B	7.1	11.9	13.0	14.5	14.6	14.6
C	4.88	6.91	7.66	7.92	8.06	7.99
D	2.13	2.91	3.18	3.29	3.33	3.35
E	1.42	1.90	2.04	2.11	2.13	2.14
F	1.07	1.24	1.28	1.28	1.26	1.25
G	0.38	0.47	0.47	0.47	0.47	0.47

D: Tunnel diameter

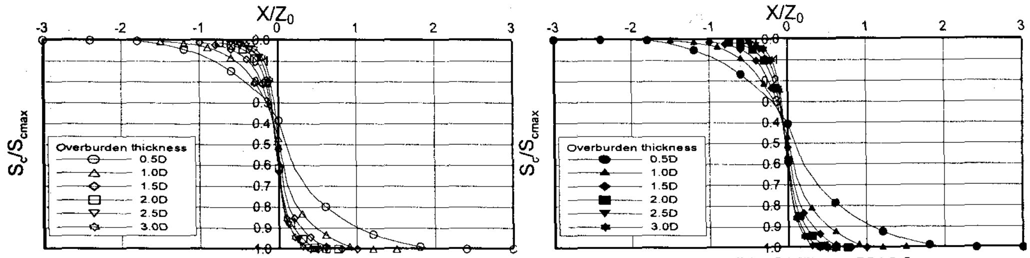
2.4 Result of numerical analysis for crown settlement

In this chapter, it was analysed the crown settlement with variation of deformation modulus and overburden thickness. Fig. 5 to Fig. 7 shows that the variation of crown settlement ratio with normalized axial distance in ground A, C, F. In Ground A which the deformation modulus of ground was 20Mpa, as being shown Fig. 6, the crown settlement ratio at the tunnel face increased little by little as the overburden thickness increase and decreased a little in case that the UAM was applied. Also, as the overburden thickness increased, the slope of crown settlement ratio curve was increased and the distance from the starting point of crown settlement was relatively increased. The ground C and ground F shows the similar tendency with the ground A, and, generally, the more the deformation modulus increased, the more the crown settlement at the tunnel face decreased.



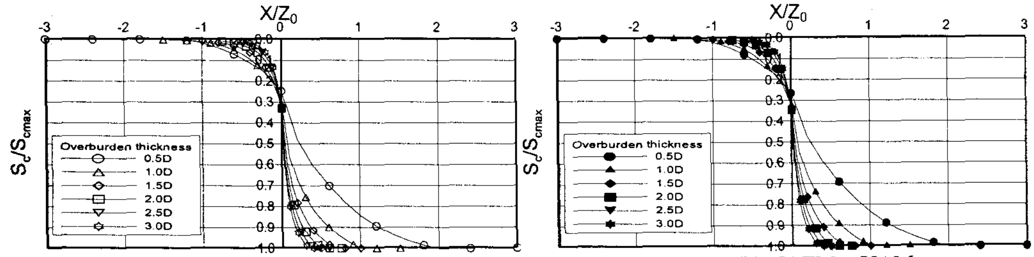
(a) NATM (b) NATM + UAM

Fig. 5. Variation of crown settlement ratio with normalized axial distance in ground A.



(a) NATM (b) NATM + UAM

Fig. 6. Variation of crown settlement ratio with normalized axial distance in ground C.



(a) NATM (b) NATM + UAM

Fig. 7. Variation of crown settlement ratio with normalized axial distance in ground F.

Table 4 and Table 5 present the maximum crown settlement(S_{cmax}) and crown settlement at the tunnel face(S_0) with variation of deformation modulus and overburden thickness as whether the UAM is applied or not. Consequently, the reinforcement effect of the UAM is more efficient in the soft ground, and as the overburden thickness increased, the crown settlement was increased. Also, as the deformation modulus of ground increased, the crown settlement ratio at the tunnel face decreased, so the restraints of ground deformation at the early stage of excavation was very important to stabilize a tunnel in soft ground which shows low capacity.

Table 5. Crown settlement with varying ground type and overburden (NATM).

Ground type	Overburden	0.5D	1.0D	1.5D	2.0D	2.5D	3.0D
A	S_0(mm)	21.0	30.1	50.1	65.4	84.0	103.3
	S_{cmax}(mm)	28.4	44.6	69.3	90.3	113.9	138.5
	S_0/S_{cmax}(%)	74.0	67.4	72.3	72.4	73.7	74.6
B	S_0(mm)	4.7	14.8	16.9	23.8	34.6	42.2
	S_{cmax}(mm)	10.7	23.4	30.5	40.9	54.0	64.8
	S_0/S_{cmax}(%)	44.0	63.1	55.4	58.3	64.1	65.2
C	S_0(mm)	2.7	5.9	9.4	15.3	20.3	17.2
	S_{cmax}(mm)	7.07	12.6	18.1	24.9	31.7	33.7
	S_0/S_{cmax}(%)	38.5	47.0	52.2	61.5	64.0	50.9
D	S_0(mm)	1.0	1.9	3.2	4.5	6.4	8.1
	S_{cmax}(mm)	3.3	5.5	7.6	10.0	12.5	15.1
	S_0/S_{cmax}(%)	28.8	35.5	41.6	45.3	50.8	53.4
E	S_0(mm)	0.5	1.1	1.7	2.4	3.1	4.1
	S_{cmax}(mm)	2.2	3.5	4.9	6.3	7.8	9.4
	S_0/S_{cmax}(%)	24.0	31.2	34.3	38.0	40.0	43.6
F	S_0(mm)	0.36	0.66	0.94	1.21	1.49	1.81
	S_{cmax}(mm)	1.5	2.2	2.9	3.7	4.5	5.3
	S_0/S_{cmax}(%)	24.7	30.8	32.4	32.9	33.1	33.9
G	S_0(mm)	0.1	0.2	0.3	0.4	0.5	0.6
	S_{cmax}(mm)	0.5	0.8	1.1	1.4	1.7	2.0
	S_0/S_{cmax}(%)	16.1	25.6	28.4	29.3	29.7	29.8

D: Tunnel diameter

Table 6. Crown settlement with varying ground type and overburden(NATM+UAM).

Ground type \ Overburden		0.5D	1.0D	1.5D	2.0D	2.5D	3.0D
A	S_0(mm)	13.3	27.5	38.6	50.0	61.5	74.4
	S_{cmax}(mm)	19.3	39.0	55.3	72.5	89.9	107.8
	S_0/S_{cmax}(%)	68.7	70.6	69.9	69.0	68.4	69.0
B	S_0(mm)	3.5	10.7	13.1	21.3	26.7	32.6
	S_{cmax}(mm)	8.2	18.2	24.9	35.4	44.0	52.7
	S_0/S_{cmax}(%)	43.2	58.7	52.7	60.4	60.7	61.8
C	S_0(mm)	2.3	4.9	7.7	11.5	15.3	16.9
	S_{cmax}(mm)	5.6	10.3	14.8	19.8	25.1	29.6
	S_0/S_{cmax}(%)	40.6	47.3	52.0	58.2	61.0	57.3
D	S_0(mm)	0.7	1.6	2.6	3.6	5.0	6.3
	S_{cmax}(mm)	2.5	4.4	6.2	8.1	10.1	12.2
	S_0/S_{cmax}(%)	29.6	36.6	42.0	44.9	49.1	51.7
E	S_0(mm)	0.4	1.0	1.5	2.1	2.7	3.3
	S_{cmax}(mm)	1.7	2.9	4.0	5.2	6.4	7.6
	S_0/S_{cmax}(%)	26.3	34.0	36.8	40.0	42.0	43.9
F	S_0(mm)	0.3	0.6	0.9	1.1	1.4	1.7
	S_{cmax}(mm)	1.2	1.9	2.6	3.3	4.0	4.7
	S_0/S_{cmax}(%)	26.5	32.4	34.0	34.5	34.7	35.3
G	S_0(mm)	0.1	0.2	0.3	0.4	0.5	0.6
	S_{cmax}(mm)	0.4	0.7	1.0	1.2	1.5	1.7
	S_0/S_{cmax}(%)	17.5	27.8	30.6	31.6	32.0	32.2

D: Tunnel diameter

3. Prediction equation of settlement

It is performed the non-linear regression analysis from the result of numerical analysis which was achieved with the deformation modulus of ground and the overburden thickness as a parameter by Levenberg-Marquadt's method and it is derived a functional formula which predicted the crown and surface settlement.

3.1 Prediction equation of surface settlement

A general shape of surface settlement by excavating a tunnel are shown in Fig.8. Where, S_{smax} is the maximum ground settlement of tunnel centre after converging, x is the lateral distance from tunnel centre, and i is the inflection point which is located with maximum inclination on the settlement curve.

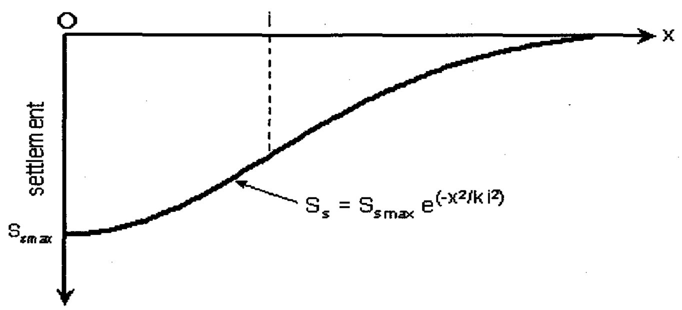


Fig. 8. A general form of transverse surface settlement.

3.1.1 Single regression analysis

In order to predict surface settlement like Fig. 9, it is performed single regression analysis from the result of numerical analysis with the following exponential function, and it is determined coefficient i and k.

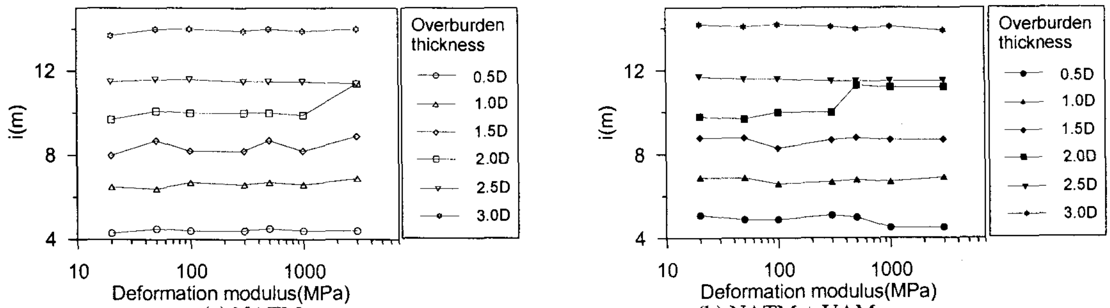
$$S_s = S_{s\max} e^{(-x^2/ki^2)} \tag{1}$$

Where, x = the lateral distance from tunnel centre.

k = a coefficient which is determined by the characteristics of ground and the overburden thickness.

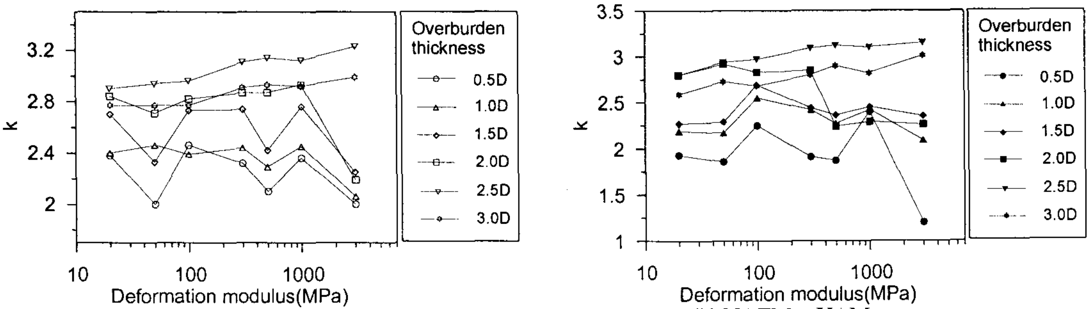
i = the inflection point which is determined by the characteristics of ground and the overburden thickness.

Fig.9,10 show the variations of inflection point i and the unknown coefficient k with increasing the deformation modulus of ground. Fig.11,12 show the variations of inflection point i and the unknown coefficient k with increasing the overburden thickness. As being shown Fig.9, the inflection point, i, of the prediction equation of surface settlement is not varied as the deformation modulus of ground increases, but it increased as the overburden thickness increased. So, i is not influenced for the deformation modulus of ground but for the overburden thickness. Hence it is performed a linear regression analysis with the overburden thickness as parameter, and as being shown Fig. 12, the coefficient of determination of inflection point is more than 0.98, that is very good result. Also, in case that the UAM is applied, i increases maximum approximately 19% than the UAM was not applied.



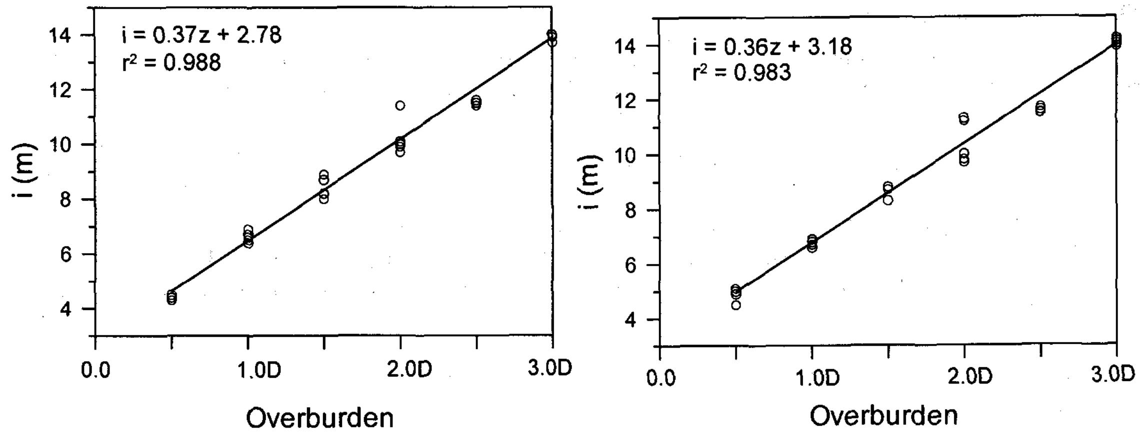
(a) NATM (b) NATM + UAM

Fig. 9. Variation of inflection point i with increasing deformation modulus.



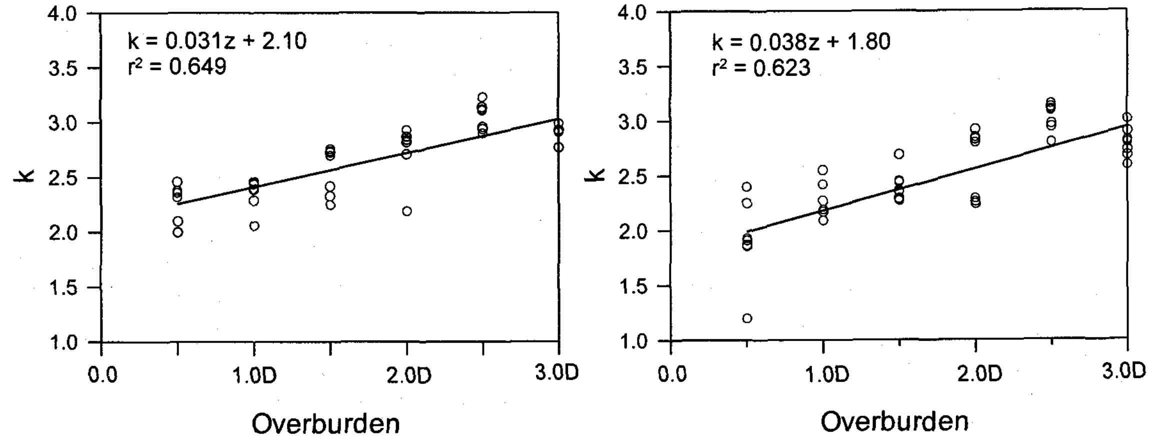
(a) NATM (b) NATM + UAM

Fig. 10. Variation of coefficient k with increasing deformation modulus.



(a) NATM (b) NATM + UAM

Fig. 11. Regression results of inflection point i with increasing overburden.



(a) NATM (b) NATM + UAM

Fig. 12. Regression results of coefficient k with increasing overburden.

The unknown coefficient k for prediction equation of surface settlement, as being shown Fig.10, was not influenced with the deformation modulus of ground, but as the overburden thickness of the tunnel crown increases, the unknown coefficient k increases. And as results of a linear regression analysis with the overburden thickness as parameter, as being shown Fig.14, a coefficient of determination was more than 0.62, and in case that the UAM is applied, k decreases to maximum approximately 22% than the case that the UAM was not applied. And, as the overburden thickness increase, the value k ranges was changelessly between 2 and 3.

3.1.2 Multiple Regression Analysis

A multiple regression analysis assumed the form of Eq.(2) which is based on results of numerical analysis for maximum surface settlement after converging in the centre of tunnel, and the multiple regression analysis is performed with overburden thickness, deformation modulus of ground and surface settlement.

$$S_{s\max}\left(\frac{1}{E},z\right)=a_s\frac{1}{E}+b_s z+c_s\frac{z}{E}+d_s \qquad (2)$$

Where, E = Deformation modulus of ground.

z = Overburden thickness from the surface to tunnel crown.

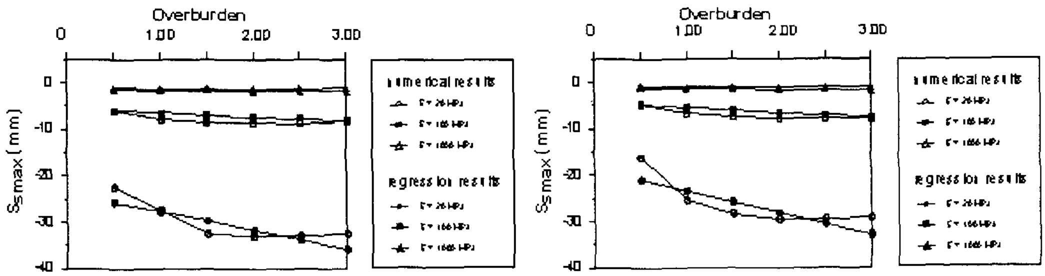
a_s, b_s, c_s, d_s = Constant is obtained from regression results.

From the result of a multiple regression analysis, in case that the UAM was not applied, the maximum surface settlement represents Eqs.(3) and its coefficient of determination was more than 0.98. In case of the UAM was applied, the maximum surface settlement represents Eqs.(4) and its coefficient of determination was more than 0.97. This is shown in Fig.13.

$$S_{s\max} = -\frac{4.51\times10^{2}}{E} - 5.31\times10^{-3}z - 8.06\frac{z}{E} - 1.15 \qquad (3)$$

$$S_{s\max} = -\frac{3.57\times10^{2}}{E} - 1.49\times10^{-3}z - 9.22\frac{z}{E} + 0.89 \qquad (4)$$

Where, S_{smax} = the maximum surface settlements(mm)
z = overburden thickness(m)
E = the deformation of soils.



(a) NATM (b) NATM + UAM

Fig. 13. Comparison of maximum surface settlement S_{smax} between the numerical and regression analyses.

3.2 Prediction of crown settlement

By excavation of the tunnel, the crown settlement curve of longitudinal direction is represented as the forms of cumulative normal distribution function or error function. Fig. 14 shows a general curve form of crown settlement. S_o indicate the crown settlement at the tunnel face and S_{cmax} indicate the maximum crown settlement after converging. If the distance(x) from the side of tunnel face indicate (-), It means the front side of tunnel face, and (+) means the back side of tunnel face.

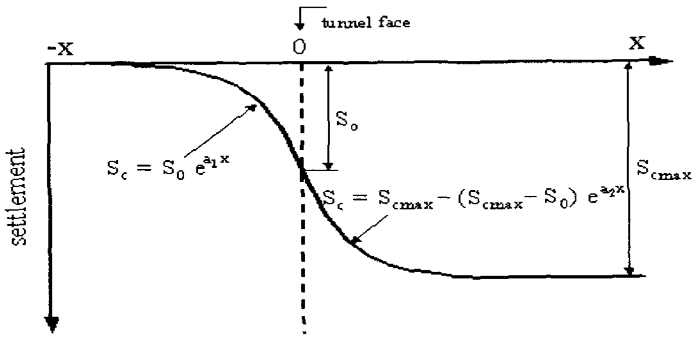


Fig. 14. A general form of crown settlement.

3.2.1 Single regression analysis

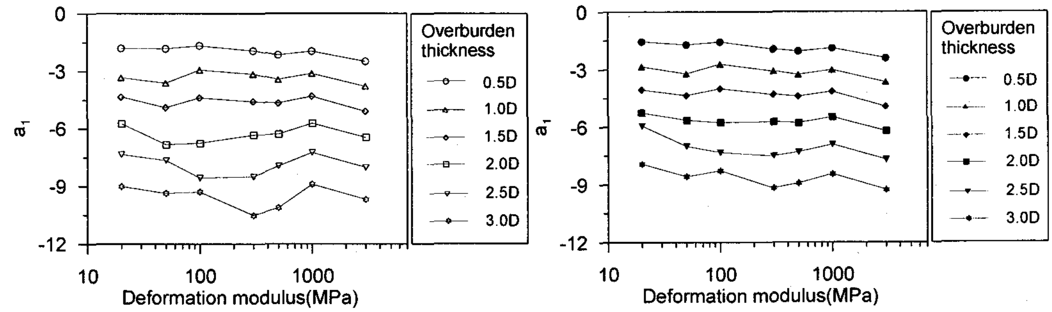
To predict the crown settlement curve, like Fig. 14, using numerical analysis result, single regression analysis was performed to the following equation which is formed a exponential function.

$$S_c = S_o e^{a_1 x} \qquad x \leq 0$$

$$S_c = S_{cmax} - (S_{cmax} - S_o)\, e^{a_2 x} \qquad x \geq 0 \qquad (5)$$

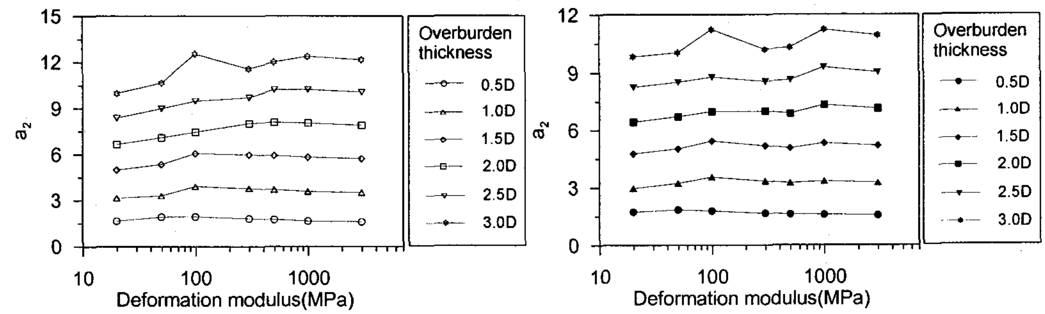
In above Eq.(5) , x=X/z, X is the longitudinal distance from the tunnel face, z is the overburden thickness from tunnel crown to the ground surface, a_1 and a_2 are the coefficient determined by the characteristic of ground and overburden thickness.

Fig. 15 and Fig. 16 present the variation of coefficient a_1, a_2 with increasing deformation modulus. Unknown coefficient a_1 and a_2 in the prediction equation of crown settlement are not influenced by deformation modulus but by overburden thickness. As the UAM is applied, a1 shows the decrease of maximum 19.0% and a_2 shows 15.7% of maximum decrease. Unknown coefficient a_1 and a_2(Fig. 17, Fig. 18) can be plotted as a linear function with overburden thickness. And the coefficient of determination is more than 0.97 and it is presented a high degree of suitability.



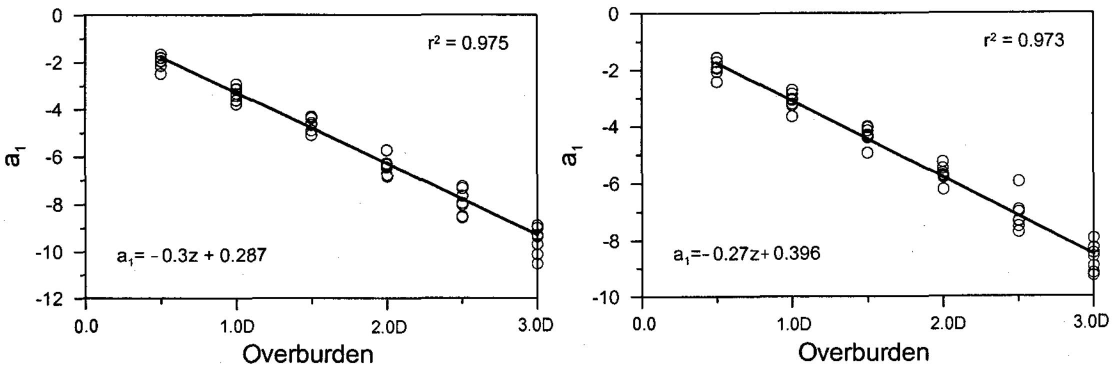
(a) NATM (b) NATM + UAM

Fig. 15. Variation of coefficient a1 with increasing deformation modulus.



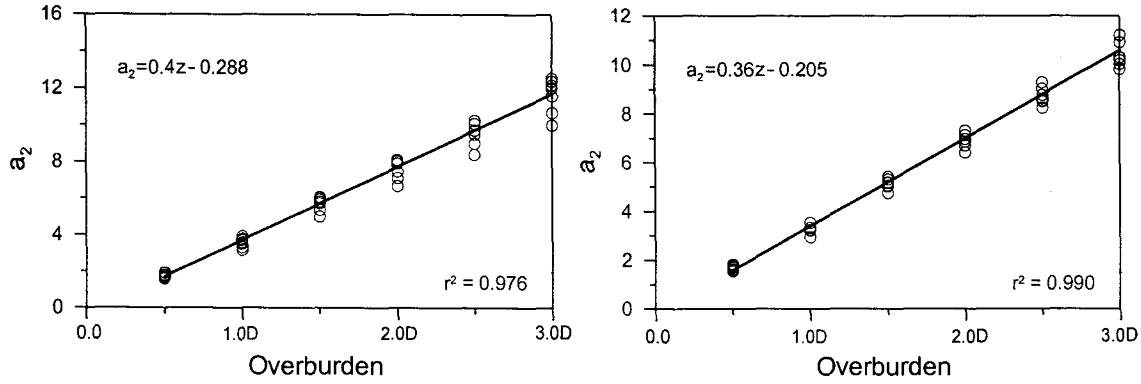
(a) NATM (b) NATM + UAM

Fig. 16. Variation of coefficient a2 with increasing deformation modulus.



(a) NATM (b) NATM + UAM

Fig. 17. Regression results of unknown coefficient a_1.



(a) NATM (b) NATM + UAM

Fig. 18. Regression results of unknown coefficient a_2.

3.2.2 Multiple Regression analysis

Based on the result of numerical analysis, the crown settlement and the maximum crown settlement after converging at the tunnel face, assumed the form of Eq.(6). And then it is performed the multiple regression analysis with overburden thickness, deformation modulus of ground and crown settlement.

$$S_0 or S_{s\max}\left(\frac{1}{E}, z\right) = a_c\frac{1}{E} + b_c z + c_c\frac{z}{E} + d_c \qquad (6)$$

In above equation, a_c, b_c, c_c, d_c, are the constant through regression analysis.

After performing multiple regression analysis, in case that the UAM is not applied, the crown settlement at the tunnel face can be presented Eq.(7) and in case that the UAM is applied, presented Eq.(8). The maximum crown settlement in case that the UAM is not applied, the maximum crown settlement can be presented Eq.(9) and in case that the UAM is applied, presented Eq.(10). The plot of that result is shown Fig. 19 and Fig. 20. At the prediction equation of crown settlement from the tunnel face, the coefficient of determination, in case that the UAM is not applied, presents 0.998, and in case that the UAM is applied, presents 0.993 as a very favourable correlation.

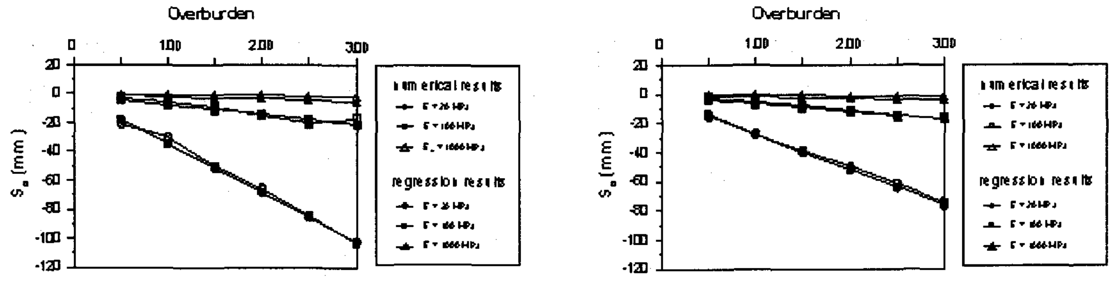
$$S_0 = -\frac{1.97}{E} - 2.28\times10^{-2}z - 6.73\frac{z}{E} - 0.482 \qquad (7)$$

$$S_0 = -\frac{46.2}{E} - 5.77\times10^{-2}z - 4.78\frac{z}{E} - 0.708 \qquad (8)$$

$$S_{c\max} = -\frac{47.5}{E} - 0.148z - 88.0\frac{z}{E} - 0.468 \qquad (9)$$

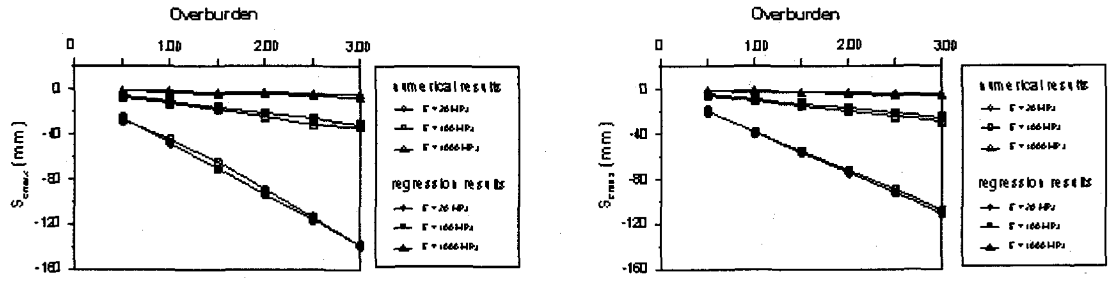
$$S_{c\max} = -\frac{47.0}{E} - 0.149z - 69.1\frac{z}{E} - 0.158 \qquad (10)$$

From the above equations, it presents that S_o is the crown settlement(mm) at the tunnel face, z_o is overburden thickness (m), and E is the deformation modulus of ground.



(a) NATM (b) NATM + UAM

Fig. 19. Comparison of crown settlement S0 between the numerical and regression analyses.



(a) NATM (b) NATM + UAM

Fig. 20. Comparison of maximum crown settlement S_{cmax} between the numerical and regression analyses.

From the regression analysis results, the surface and the crown settlement at the shallow and soft ground, as the tunnel excavation is processed, can be expressed as exponential function shown equation (1) and (5) with the deformation modulus and overburden thickness as parameters. Maximum surface settlement, maximum crown settlement and the crown settlement at the tunnel face can be generalized as equation (11).

$$S\left(\frac{1}{E},z\right)=a\frac{1}{E}+bz+c\frac{z}{E}+d \qquad (11)$$

In here, a, b, c, and d are constants determined by the regression analysis.

5. Conclusion

In this study, it was performed the 3-dimentional Finite Element Analysis in the soft ground where UAM was applied, and whether the UAM is applied or not, it was analysed the decrease of ground deformation and the reinforcement effect. And it is deduced the equations, which could predict the crown settlement and surface settlement as tunnel excavation, from the ground properties expressed as deformation modulus and the study of parameters related to the overburden thickness of tunnel crown, and the regression analysis. From this study, The results could be summarized as follows.

Whether the UAM was applied or not, the result of settlement analysed showed that reinforcement effect of UAM was efficient to the soft ground and the small overburden thickness. And as the settlement ratio at the stage of upper half excavation increase to the soft ground, it was found that the repression of ground deformation was really important to secure the stability of tunnel.

In case that the UAM is applied, it increased the location of inflection point which indicate the settlement range. And the settlement ratio at the location of inflection point is not nearly related with the deformation modulus of ground but related with the overburden thickness. In case that the UAM is not applied, the settlement ratio at the location of inflection point is presented from 0.61~0.73. It shows a little high ratio compare to the existing study where presented as 0.61. Also, considering a survey error to measurement in the field, 3.0i point can be possibly accepted as a limit of settlement range instead of 2.5i point.

As the result of single regression analysis to deduce the prediction equation of surface settlement, the unknown coefficient i and k relating with the overburden thickness plotted as linear function and the coefficient of determination was more than each 0.98 and 0.62. Depending on the UAM applied or not, the coefficient of determination was presented as each 0.97 and 0.98 at a high suitability. From the result of single regression analysis to deduce the prediction equation of surface settlement, the unknown coefficient, a_1 and a_2 which was not related with deformation modulus but with overburden thickness, and its coefficient of determination presented more than 0.97. Depending on UAM applied or not, from the result of multiple regression analysis, the coefficient of determination presented more than 0.99 at a high suitability.

In conclusion, the prediction equation of longitudinal crown settlement and transverse surface settlement as the tunnel excavated, can be expressed as an exponential function of which parameter is deformation modulus of ground and the overburden thickness. Through that equation, it is possible to predict the settlement at the time of design stage, and before executing tunnel excavation. And also using that equation, these are expected ; The reinforcement effect of UAM, the stability of tunnel itself, the estimation of stability to the adjacent ground constructions.

References

1. Kim, S., H., 2003, A Study on the Reinforcement Effect of Umbrella Arch Method and Prediction of Tunnel Crown and Surface Settlement, Ph D. thesis, Hanyang University, p136.
2. Kim, G., J., Moon, H., K., 2001, A Theoretical and Numerical Study on the Effects of Prereinforced of Tunnel Face, TUNNEL & UNDERGROUND, J. of Korean Society for Rock Mech., Vol. 11, No.4, pp328-338.
3. Kim, C., Y., Bae, G., J., Moon, H., K., Choi, Y., K., 1998, A Study on the 3-dimentional Finite Element Analysis for the Tunnel Reinforced by Umbrella Arch Method., TUNNEL & UNDERGROUND, J. of Korean Society for Rock Mech., Vol. 8, No.3, pp.209-225.
4. Bae, G., J., Kim, C., Y., Moon, H., D., Hong., S., Y., 1997, A Study on the Ground Movement around Tunnel Reinforced by Umbrella Arch Method, TUNNEL & UNDERGROUND, J. of Korean Society for Rock Mech., Vol. 7, No.4, pp.299-309.
5. Harazaki, I., Aono, H., Matsuda, A., Aoki, T. and Hakoishi, Y., 1998. "Field observation of large tunnel supported by umbrella method: Case of Maiko Tunnel in Kobe, Japan", Proc. of the World Tunnel Cong. 98 on Tunnels and Metropolises, Vol. 2, pp. 1009-1014.
6. Pelizza, S. and Peila, D. and Oreste, P. P., 1994, "A new approach for ground reinforcing design in tunnelling, soil and rock reinforcements", Tunnelling and Ground Conditions, Abdel Salem(ed), Balkema, pp. 267-271.
7. Panet, M., and Guenot, A., 1982, "Analysis of convergence behind the face of a tunnel", Tunnelling 82, IMM, Brighton, pp. 197-204.
8. Shirakawa, K., Aoki, T., Fujii, Y. and Nakao, T., 1999. "Excavation through semicircular- shaped shell formed by umbrella method at fault fracture zone beneath densely residential area", Proc. of the World Tunnel Cong. 99 on Challenge for the 21st Century, Vol. 1, pp. 441-447.