Underground Space Use: Analysis of the Past and Lessons for the Future – Erdem & Solak (eds)

Surface settlement prediction for Istanbul metro tunnels via 3D FE and empirical methods

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ABSTRACT: In this study, surface settlement is predicted for tunnels which are to be excavated in the section of 5 + 635–5 + 735 meters between Sehzadebasi and Yenikapi stations of Istanbul Metro line. Precautions in order to minimize the ground settlement are also suggested. Geology in this section is composed of clay, claystone, sand and marl. Tunnels, 36 m^2 in cross-section, are excavated employing NATM method. Umbrella method of pre-excavation and shotcrete for temporary support are employed. Between crown and bench excavation, a 2.40 meter distance is kept constant. Settlement prediction is made with 2 different methods, empirical and 3D finite element method. Empirical method is based on Gaussian curve suggested by O'Reilley. For 3D finite element, 3D Tunnel program is used. For 3D analysis, excavation and ground reinforcement steps are simulated exactly as applied in the field. The results of 2 methods are found to be in good agreement.

1 INTRODUCTION

Istanbul Metro line has been constructed in 2 phases. The first construction phase was started in 1992 and opened to public in 2000. The second phase between Taksim and Yenikapi is under construction by Anadolu Metro joint venture. The route of metro line phases 1 and 2 are shown in Figure 1.

1.1 *The geology*

Trakya formation of the Carboniferous age is found in the study area consisting of fine-grained, laminated, fractured and interbedded siltstone, sandstone and mudstone. A formation locally named Suleymaniye overlays Trakya Formation. Suleymaniye Formation includes competent or deformed claystone and marl with interbedded clay and sand horizons. Some diabase or andesite dykes are also encountered. Many faults and geologic discontinuities exist in the area due to Hercinian and Alpine Orogenies. The overburden thickness above the tunnels varies between 17 to 25 meters, averaging 21.5 meters.

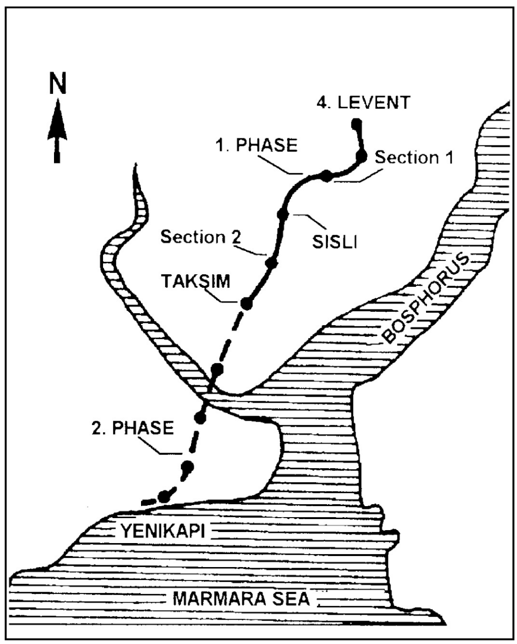

Figure 1. Main route of Istanbul metro line.

1.2 *Method of construction*

New Austrian Tunneling Method (NATM) is used in the study area of Type A tunnel. Currently used temporary tunnel support includes 4 to 6 m long rock bolts, wire mesh and shotcrete. Prior to excavation, an umbrella of steel pipes are installed with a 5^0 dip in a truncated conic shape made on the crown of the tunnel. Umbrella length is 9 m of which excavation is carried on under 6 m. Truncated cone shape allows the 3 m overlapping of two adjacent umbrellas.

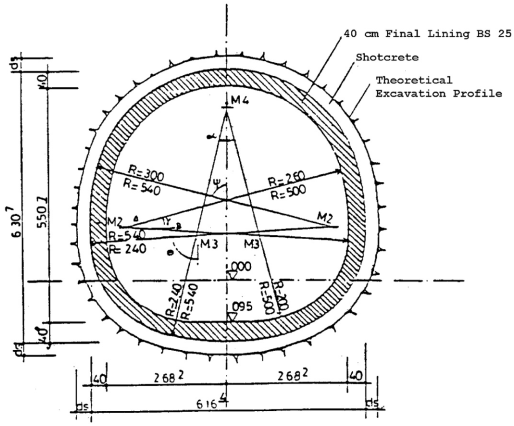

Figure 2. Typical cross section of single track tunnel, Type A.

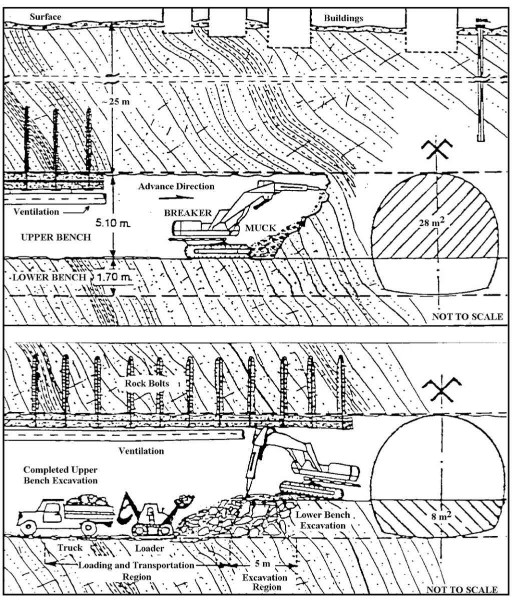

Figure 3. Method of construction in Istanbul Metro tunnels (Bilgin, 2002).

Depending on tunnel diameters, the final lining is undertaken with 35 to 45 cm thick in-situ cast concrete. Type A tunnel (Figure 2) has a cross-section of 36 m^2 and the upper half of 28 m^2 is excavated first and the lower part is excavated later which is 2.40 m behind the upper part (Figure 3).

There are mainly two settlement prediction approaches: (i) empirical, based on empirical formulas derived from past observations, (ii) numerical

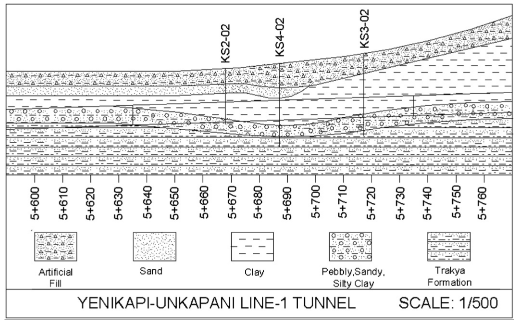

Figure 4. Geological cross-section.

analysis such as finite element approach, which is the most popular method. In this study, both methods are employed to predict the surface settlement above the tunnels of the chainage between 5 + 635 m and 5 + 735 m of phase 2 of line 2. A new excavation sequence and support system are recommended in order to prevent the damage to the nearby buildings. This section has the most difficult ground conditions. Geological cross-section of the study area is presented in Figure 4. Laboratory and in-situ tests are applied to define the geotechnical features of the formations tunnels passed through. Summary of the geotechnical properties are presented in Table 1.

2 EMPIRICAL PREDICTIONS

Settlement parameters used in empirical estimations and notations are presented in Figure 5. Assumptions used in the estimations are as follows:

- Cross-section of the tunnel is circular.
- Tunnel is shallow.
- Tunnel passes through clay formation.
- Tunnelling method is NATM.
- Estimations are valid for completed primary support (wire mesh + shotcrete + bolts + lattice).
- Since the excavation of other tunnel next to 35 m is completed, the settlement interaction between the tunnels is ignored.
- Long term consolidation settlement is ignored.

Equations used in estimations are as follows:

$$S = S_{\max} \cdot e^{\left(\frac{-x^2}{2 \cdot i^2}\right)} \qquad \text{(O'Reilley, 1982)} \qquad (1)$$

$$i = \frac{i_1 + i_2 + i_3}{3} \qquad (2)$$

$$i_1 = 0.386 \cdot Z_0 + 2.84 \qquad \text{(Arioglu, 1992)} \qquad (2a)$$

Table 1. Geotechnical properties of formations.

Strata	Unit weight (kN/m^3)	Elastisity Modulus (kN/m^2)	Cohesion (kN/m^2)	Poisson Ratio	Angle of Friction
Fill	18.0	5,000	1.0	0.40	10
Sand	17.0	15,000	1.0	0.35	25
Süleymaniye formation	18.9	38,000	20.0	0.33	14
Tarkya formation	25.0	60,000	80.0	0.20	25

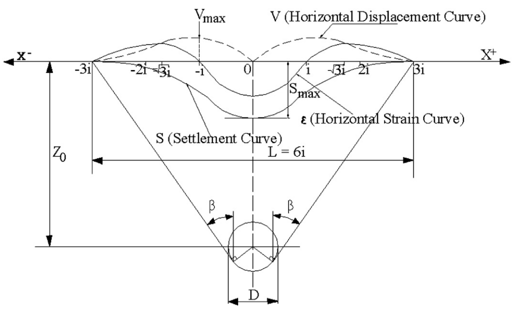

Figure 5. Settlement parameters and notation.

$$i_2 = 0.5 \cdot Z_0 \quad \text{(Glossop, 1978)} \tag{2b}$$

$$i_3 = 1.392 \cdot \left(\frac{D}{2}\right) \cdot \left(\frac{Z_0}{D}\right)^{0.704} \quad \text{(Arioglu, 1992)} \tag{2c}$$

$$S_{max} = 0.785 \cdot (\gamma \cdot Z_0 + P_s) \cdot \left(\frac{D^2}{i \cdot E}\right) \text{(Herzog,1985)} \tag{3}$$

$$ds/dx = 0.606 \cdot (S_{max}/i) \quad \text{(O'Reilley, 1982)} \tag{4}$$

$$d^2s/dx^2 = 0.445 \cdot (S_{max}/i) \quad \text{(O'Reilley, 1982)} \tag{5}$$

$$\varepsilon_t = 0.445 \cdot \left(\frac{S_{max}}{Z_0}\right) \quad \text{(O'Reilley, 1982)} \tag{6}$$

$$\varepsilon_c = 0.445 \cdot \left(\frac{S_{max}}{i^2}\right) \quad \text{(O'Reilley, 1982)} \tag{7}$$

$$H_{mx} = i \cdot \sqrt{3} \quad \text{(O'Reilley, 1982)} \tag{8}$$

where,

S = theoretical settlement (gauss error function, normal probability curve)

Table 2. Building damage classification.

ds/dx	S_{max} (mm)	Damage
<0.002	<10	Ignored
0.002–0.005	10–50	Slight
0.005–0.02	50–75	Medium
>0.02	>75	High

S_{max} = maximum settlement (m)
x = transverse horizontal distance from the tunnel center line (m)
i = point of inflexion (m)
Z_0 = tunnel axis depth (m)
D = equivalent tunnel excavation diameter (m)
γ = natural unit weight of formation (ton/m^3)
E = elasticity modulus of formation (ton/m^2)
P_s = total surcharge load (ton/m^2)
ds/dx = maximum slope
d^{2}s/dx^2 = maximum sagging curvature
ε_t = maximum horizontal strain (tensile) (m)
ε_c = maximum horizontal strain (compressive) (m)
H_{mx} = point of maximum curvature (m).

Equations (2) and (3) were derived from both shield excavated and NATM tunnel data (Arioglu, 1992). Other equations (4, 5, 6, 7, 8) were derived theoretically from the theoretical settlement function given in Equation (1), (O'Reilley, 1982).

Damage to the buildings due to settlement can be classified as in Table 2, (Attewell et al., 1986).

Input parameters and results of the empirical settlement predictions for Yenikapi-Unkapani Line-2 tunnel previously excavated in Trakya Formation are presented in Table 3. As it is seen, the maximum settlement and maximum slope values are 37 mm and 0.002, respectively, and possible level of damage to the nearby buildings is slight.

In-situ settlement and building displacement measurements are performed on ground surface and

Table 3. Settlement prediction for Yenikapi-Unkapani Line-2 Tunnel in Trakya formation.

Input	Estimations (m)
$D = 6.77\,\text{m}$	$i = 10.2$
$Z_0 = 20.0\,\text{m}$	$S_{\max} = 0.0370$
$\gamma = 2.50\ \text{tonne/m}^3$	$\mathrm{d}s/\mathrm{d}x = 0.0022$
$E = 6000\ \text{tonne/m}^2$	$\mathrm{d}^2s/\mathrm{d}x^2 = 0.0016$
$P_s = 13.0\ \text{tonne/m}^2$	$\varepsilon_t = 0.0008$
Building Damage: Slight	$\varepsilon_c = 0.0004$
	$H_{mx} = 17.7$

Table 4. Results of surface settlement measurements for Yenikapi-Unkapani Line-2 tunnel in Trakya formation.

Street	Behnameci				Azimkar
Point	Y-5093	Y-5095	Y-5105	Y-5103	Y-5119
S (m)	0.012	0.024	0.016	0.010	0.044
x (m)	18	9	6	11	6
i (m)	10.2	10.2	10.2	10.2	10.2
S_{mak} (m)	0.057	0.035	0.019	0.018	0.052
% diff.*	+54	−5	−49	−51	+41

* Percent difference from predicted value of 0.037 m.

different buildings in Yenikapi-Unkapani Line-2 tunnel to validate the empirical method. The results of settlement measurements are summarized in Table 4 and Figure 6. As seen, the empirical predictions are lower than the measured settlements in some cases and higher in others. However, overall the empirical predictions can be assumed to be approaching to actually occurred settlements. Displacement measurements performed on surface and different buildings validate the empirical model. Therefore, it is also possible to use the empirical method for settlement predictions to be occurred in Yenikapi-Unkapani Line-1 tunnel to be excavated later in Suleymaniye Formation.

Input parameters and results of the empirical settlement predictions for Yenikapi-Unkapani Line-1 Tunnel (between chainage 5 + 635 and 5 + 735) to be excavated in Suleymaniye Formation are presented in Table 5 for the worst case ($E = 2000$ tonne/m^2) and Table 6 for the best case ($E = 3000$ tonne/m^2). As seen, the predicted maximum settlements are around 88 mm (with maximum slope of 0.0052) for the worst case and 59 mm (with maximum slope of 0.0035) for the best case. Possible levels of damage to the near buildings are medium for the worst case and slight for the best case. Variation of maximum settlement versus elasticity modulus is presented in Figure 7.

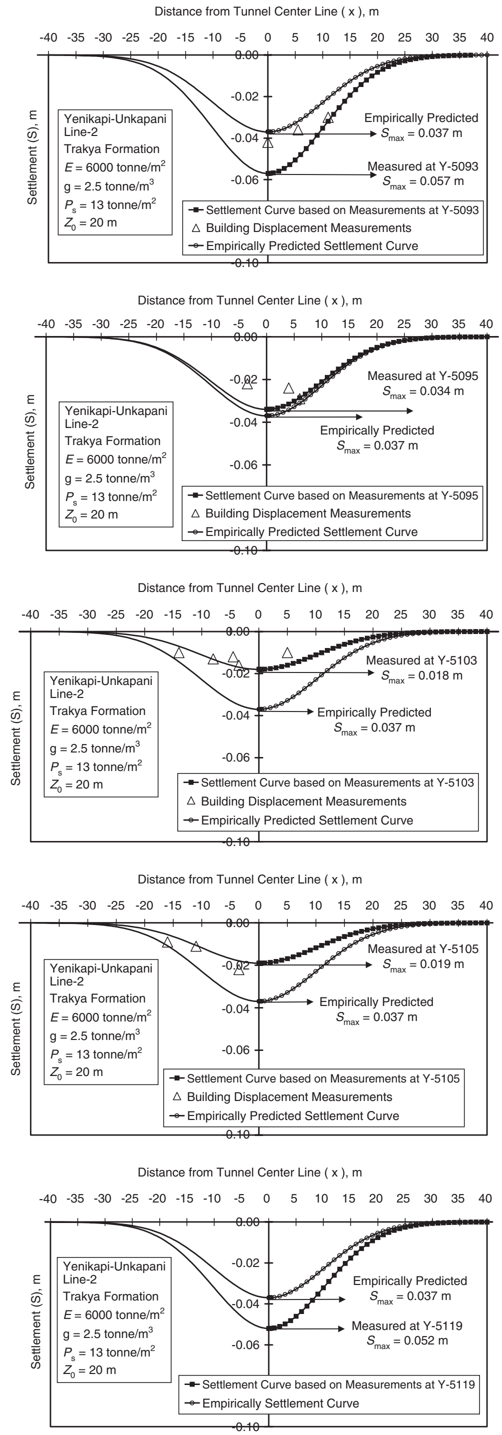

Figure 6. In-situ surface settlement and building displacement measurements in Yenikapi-Unkapani Line-2 tunnel.

Table 5. Settlement prediction for Yenikapi-Unkapani Line-1 tunnel in Suleymaniye formation (the worst case).

Input	Estimations
D = 6.77 m	i = 10.2 m
Z_0 = 20.0 m	S_{max} = 0.0884 m
γ = 1.86 tonne/m^3	ds/dx = 0.0052
E = 2000 tonne/m^2	d^2s/dx^2 = 0.0038
P_s = 13.0 tonne/m^2	ε_t = 0.0020 m
Building Damage: Medium	ε_c = 0.0008 m
	H_{mx} = 17.7 m

Table 6. Settlement prediction for Yenikapi-Unkapani Line-1 tunnel in Suleymaniye formation (the best case).

Input	Estimations
D = 6.77 m	i = 10.2 m
Z_0 = 20.0 m	S_{max} = 0.0589 m
γ = 1.86 tonne/m^3	ds/dx = 0.0035
E = 3000 tonne/m^2	d^2s/dx^2 = 0.0026
P_s = 13.0 tonne/m^2	ε_t = 0.0013 m
Building Damage: Slight	ε_c = 0.0006 m
	H_{mx} = 17.7 m

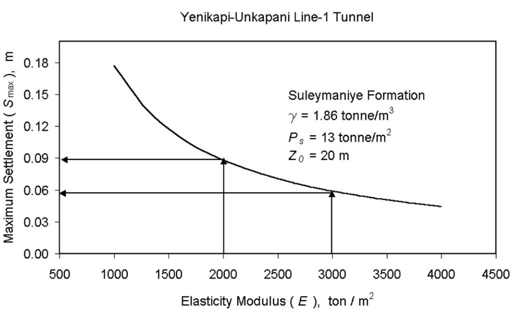

Figure 7. Variation of settlement according to elasticity modulus for Yenikapi-Unkapani Line-1 tunnel in Suleymaniye formation.

3 3D FINITE ELEMENT MODELLING

An important concern of tunnelling is the development of surface settlements. As for the tunnel heading stability, a 3D analysis is needed for a proper prediction of surface settlement. To investigate its development, 3D Finite Element model analysis is performed. For this analysis, Plaxis 3D Tunnel program is used. 3D Tunnel program is capable of simulating staged excavation sequences as in NATM tunnelling. Using this program, the NATM tunnel with a cross-section of 36 m^2 and a cover of around 20 m is modelled with an unsupported excavation length of 0.60 m. Each phase consists of 0.60 m of excavation. Within the same phase, a shotcrete lining and rock bolts are applied to support the previous excavation. Umbrella system is activated previous to excavation. The shotcrete lining has a thickness of 30 cm and rock bolts are 4 to 6 m in length.

Table 7. Properties of support system

Item	Elastisity modulus (kN/m^2)	Poisson ratio	Normal stiffness (kN/m)	Flexural rigidity (kNm^2/m)
Young shotcrete	1.0×10^7	0.2		
Hard shotcrete	2.85×10^7	0.2		
Rock bolt			2×10^5	
Umbrella		0.2	5.7×10^6	19,950

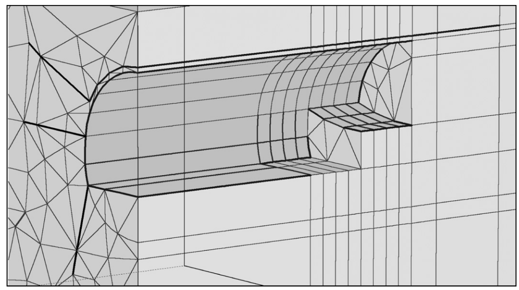

Figure 8. Partial FE model.

3D model is chosen because for 2D FE models, it is not so easy to estimate pre-relaxation factors (sometimes called stress reduction factors), which is fraction of load effecting on tunnels, and purely based on practical experience. With the 3D model, estimation of pre-relaxation factor is no longer required when excavation stages can be modelled not only in cross-section but also in the longitudinal section, e.g. excavation of the bench and invert can be modelled in the actual distance behind the excavation of the top heading. A typical sequential tunnel excavation in accordance with the principles of the New Austrian Tunnelling Method is modelled more realistically by the 3D FE. The model involved modelling of the ground, shotcrete, bolting and umbrella. Shotcrete time dependent behaviour is modelled in such a way that two sets of parameters for the shotcrete, young and hard, has been included. When placing the lining for the first time, the young is assigned to the lining and for the next excavation step this is changed to hard.

The physical properties of supporting system, including umbrella, bolting and shotcrete, used in the calculations are shown in Table 7.

The FE model consists of 11,936 elements and 34,140 nodes. Figure 8 shows the partial finite element

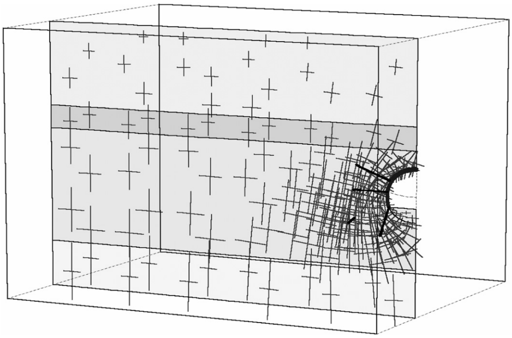

Figure 9. Stress arc after bench excavation.

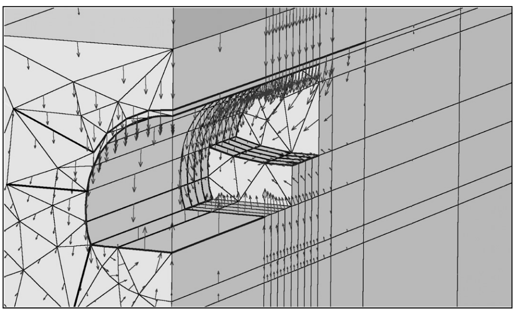

Figure 10. Total displacement vectors around tunnel.

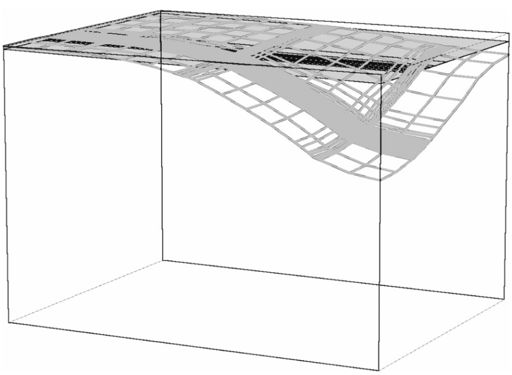

Figure 11. Settlement profile in the shape of Gaussian curve.

model at a later excavation stage with the top heading advancing.

The thickness of slices in 3D model are chosen according to the distance between the excavation steps, 0.60 m, and the actual distance between the excavation faces of top heading and bench, 2.40 m. Invert excavation and final lining are not modelled in the numerical model.

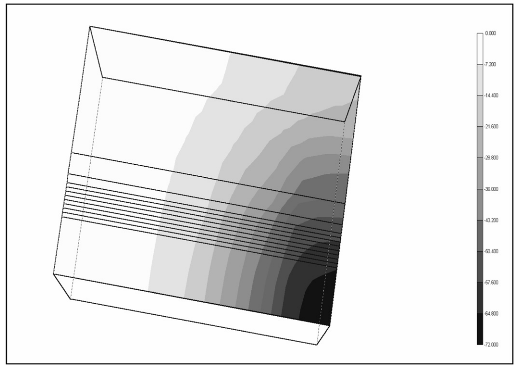

Figure 12. Settlement contours on the surface.

As the result of analysis, stress arc acting around the tunnel after bench excavation is shown in Figure 9, and total displacement vectors are shown in Figure 10.

The maximum ground settlement is estimated as 54.4 mm after 2.40 m of top heading and 72.7 mm after the bench excavation. Corresponding total tunnel closure is calculated as 130 mm. Vertical displacement profiles on the surface, when bench advances, are shown in Figures 11 and 12. In Figure 11 settlement profile in the shape of Gaussian curve is clearly evident. Maximum settlement is directly above the tunnel axis.

4 CONCLUSIONS AND SUGGESTIONS

Surface settlement is predicted for tunnels which are to be excavated in the section of 5 + 635 to 5 + 735 meters between Sehzadebasi and Yenikapi stations of Istanbul Metro line using two settlement prediction approaches. This section has very difficult ground conditions. Empirical method resulted as the maximum settlement will be between 59 and 88 mm. Numerical method predicted the maximum ground settlement about 72.7 mm. As seen the results of two methods are to be in close agreement.

Although possible levels of damage to the nearby buildings are in medium level, this can not be acceptable. Therefore, precautions to reduce the surface settlement are suggested. First suggestion is the ground improvement before excavation. Among the ground improvement techniques, jet grouting is found to the most applicable technique in this particular tunnelling section. Since grouting from surface is very difficult because of the buildings, it is suggested that it should be applied from the existing shaft where possible or from the inside of the tunnel prior to the excavation. It is also suggested that underpinning should be applied to the buildings where the foundation is weak.

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