Aalborg Universitet

Analysis of an Underground Structure Settlement Risk due to Tunneling

A case study from Tabriz, Iran

Vahdatirad, Mohammad Javad; Ghodrat, Hadi; Firouzianbandpey, Sarah; Barari, Amin

Original Article

Analysis of an underground structure settlement risk due to tunneling- A case study from Tabriz, Iran

Mohammad Javad Vahdatirad[1]*, Hadi Ghodrat[2], Sara Firouzian[1] and Amin Barari[3]

[1] Department of Civil Engineering,
Babol University of Technology, Babol, Iran

[2] Faculty of Engineering,
Tarbiat Moallem University, Tehran, Iran

[3] Department of Civil Engineering,
Aalborg University, Sohngårdsholmsvej 57, 9000 Aalborg, Aalborg, Denmark

Abstract

The tunnel of the Tabriz urban railway line 2 (TURL2), Iran, will pass through an underground commercial center on its way. Too little distance between the tunnel crown and the underground structure foundation will probably cause collapse or excessive settlement during the tunnel construction based on studied geotechnical conditions of the region. In this paper, a method of risk level assessment for various types of structures, such as frame and masonry structures, and various types of foundation, such as continuous and isolated, is well defined and the risk level is classified. Moreover, the value of the underground commercial center structure settlement is estimated using both empirical and numerical methods. The settlement risk level of the commercial center structure is determined based on presented definitions about risk classification of various types of structures. Consequently, tunneling processes in this section need a special monitoring system and consolidation measures before the passage of a tunnel boring machine.

Keywords: settlement, risk assessment, tunneling, empirical method, numerical method

1. Introduction

Tabriz is one of the crowded and important cities in northwestern Iran, with a 160 km^2 spatial size and a population of about 1,360,000. According to previously carried out traffic and transportation studies four light urban railways with a length of 48 km (extendable to 72 km) are considered for this city (Figure 1). Studies and design of the Tabriz urban railway line 2 (TURL2) were started in 2006. TURL2, with the length of 20 km, will connect the eastern part of the city with the western one and will pass populated parts of the city, like trading centers, on its way. In the city center, the crown of the TURL2 tunnel has been excavated applying a mechanized method using an EPB-TBM with a diameter of 9.2 m that passes under commercial structure foundations with the distance of about 13.1 m (Figure 2). The foundation of the commercial center with the thickness of 1.5 m is located at 5.86 m depth (Figure 3). Based on previously studied geotechnical conditions of the region including the material, consisting low cohesion and medium density, and the shallow water table, it is of great importance to further carry out a settlement risk analysis.

The problem of tunnel-induced settlements and related risk assessments of building damages has interested
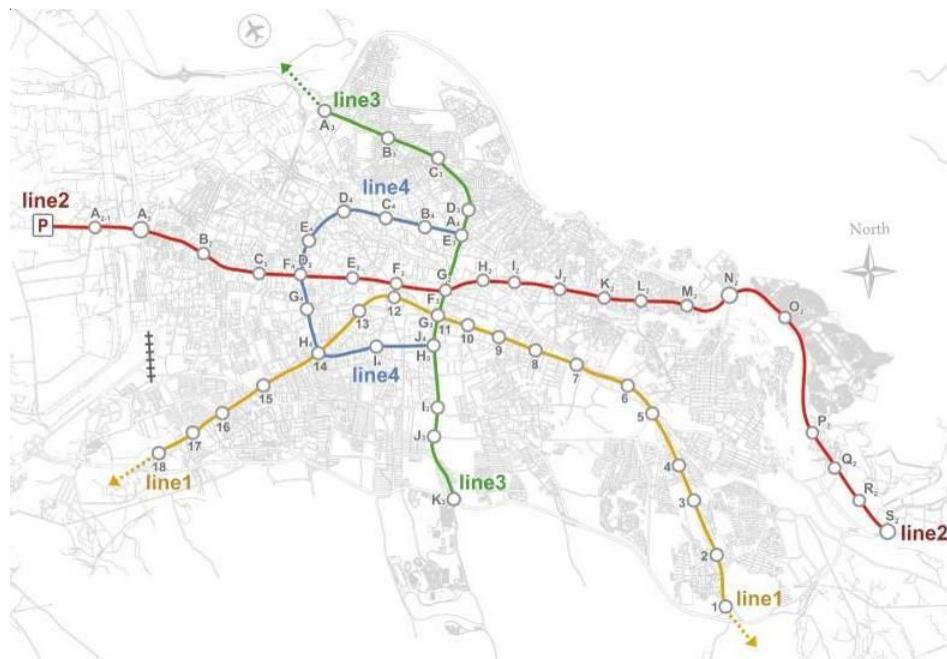
Figure 1. Tabriz urban railway system.

Figure 2. Underground commercial center plan in TURL2 corridor.

many researchers over the last 40 years. Many references are presented, among others, Peck, 1969; Cording *et al.*, 1975; Burland *et al.*, 1977; Attewell *et al.*, 1982, 1984; Rankin, 1988; Boscardin and Cording, 1989; Clough and O'Rourke, 1990; New and O'Reilly, 1991; Leblais *et al.*, 1995; Mair *et al.*, 1996, 1997. Zaw Zaw *et al.* (2006) presented methods that were adopted in the prediction of excavation and tunneling induced ground movement and building damage risk-assessment for the first underground mass transit system project of Bangkok. The measured ground and associated movement of the buildings and structures were within predicted values. Moreover, Selby (1988) used numerical modeling to study transmission of settlements upwards to the surface in a homogeneous medium and in a layered medium with different consistency of the strata. Attewell and Woodman (1982) presented the most common available methods for the assessment of the Greenfield movements due to tunneling for the case of a single-tube tunnel in a homogeneous medium.

Figure 3. Underground commercial center section.

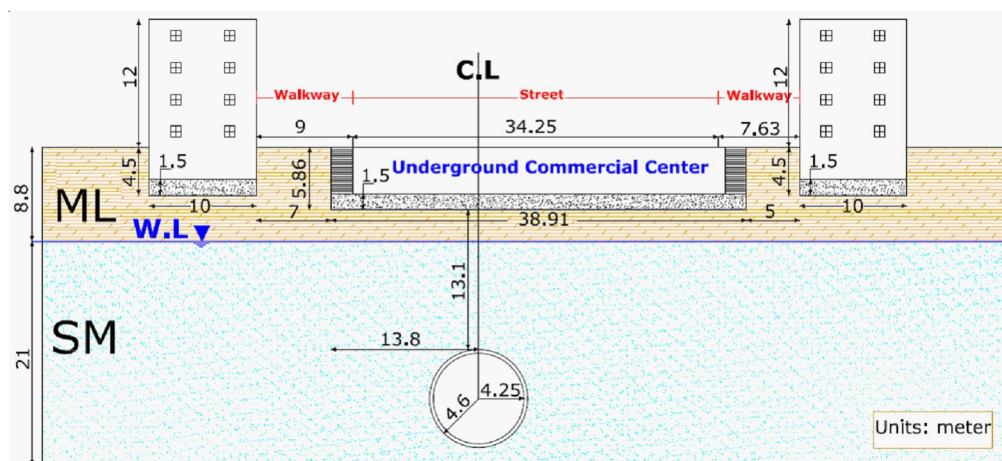Also, the semi-empirical Gaussian curve expressing the long-term 'Greenfield' settlements is obtained by Peck (1969) from over 20 case histories and it represents the subsidence trough in a transverse section well behind the tunnel face, where maximal displacement due to tunneling are already achieved.

In the current research, according to performed studies including settlement prediction and related risk analysis, the settlement risk level of an underground commercial structure in the rout of the Tabriz urban railway is determined. A classification of buildings settlement risks was adopted. Settlement calculations of commercial centre foundations were performed applying empirical and numerical methods using the PLAXIS finite element software code.

Finally, the settlement risk level of the commercial center structure is determined based on presented definitions on risk classification of various types of structures.

2. Concept and categorization of risk

For structures with continuous foundation, the limit values for deformation are given by Burland *et al.* (1977) defining different risk category based on the cracks present in the structure. In addition, for structures with isolated foundations the classification is given by Rankin (1988), which fixes limit values for settlement and angular deformation. In order to simplify the damage estimation and the nomenclature the Burland (1977) and Rankin (1988) risk categories have been summarized as shown in Table 1. In Table 1, the quantity of damage is classified as below:

- *Aesthetic damages* are related to slight cracking of the structures, affecting mainly the internal walls and their finishes. These effects shall be repaired easily.

- *Functional damages*: the damages cause the loss of functionality of parts of the structure or of instruments

Table 1. Relation between risk categories and counter-measures.

Risk category (*Burland*)	Measures to be applied before and/or during the excavation	Risk category (*Rankin*)
0 (aesthetic)	Any requirement	1 (aesthetic)/ **Negligible**
1 (aesthetic)		
2 (aesthetic)	Monitoring of the building and activation of the counter-measures if necessary	2 (aesthetic)/ **light**
3 (aesthetic /functional)	Safety measures (grouting or structure consolidation) to be realized before the execution of the new construction. Monitoring of the building and activation of the counter-measures if necessary	3 (functional)/ **medium**
4 (functional)		
5 (structural)		4 (structural)/ **high**

installed inside. This should have a strong impact in terms of financial costs.

- *Structural* damages: cracking or high deformation of structural elements. There should be a collapse risk of the structure, for parts of it or for the overall building.

In this case it is necessary to underline that both the classification proposed by Burland (1977) and Rankin (1988) are referred to buildings in good condition. This limit value shall be updated taking into account the vulnerability index of the buildings in the next section.

3. The vulnerability index I_v

The construction of new underground structures can cause in the existing building deformation modes different from the ones that were previously normal for it. For this reason, the new deformations possibly induced are added to the previous ones and a very light new deformation can be critic if the previous deformations were important. Therefore, it is necessary to evaluate the conditions of the building before the construction of a new underground structure. For this reason, the vulnerability is defined as the intrinsic characteristic of the building that expresses the state of the building and its vulnerability. The vulnerability is evaluated by a direct and bibliography investigation of the buildings

present on the line called Building Condition Survey (BCS).

The characteristics of the building must be collected based on the following themes:
- Structural behavior (kind of structure, number of floors, dimension of the building),
- Kind of foundations,
- Functionality and use of the building,
- State of conservation of the building,
- Orientation with reference to the tunnel excavation axis.

For each item, a different weight is assigned and the sum represents the vulnerability index of the building. Low values of the vulnerability mean higher capacity of the building to resist to deformation. Table 2 shows a correlation between the threshold values by the Rankin and Burland formulation and the risk categories through a vulnerability index evaluation.

4. Threshold values

Once the risk category has been evaluated it shall be defined if the building needs special consolidation measures or monitoring during construction. There are three possible categories of actions listed in Table 3. These actions are associated to different risk categories.

Table 2. Correlation between the threshold values by Rankin and Burland formulation and risk categories through vulnerability index evaluation (Chiriotti 2000).

Category of Damage	Negligible $0 < I_V < 20$		Low $20 < I_V < 40$		Slight $40 < I_V < 60$		Medium $60 < I_V < 80$		High $80 < I_V < 100$	
	Control Parameter									
	$S_{max}(mm)$	β_{max}	$S_{max}(mm)$	β_{max}	$S_{max}(mm)$	β_{max}	$S_{max}(mm)$	β_{max}	$S_{max}(mm)$	β_{max}
1	<10	<1/500	<8	<1/625	<6.7	<1/750	<5.7	<1/875	<5	<1/1000
2	10-50	1/500-1/200	8-40	1/625-1/250	6.7-33	1/750-1/300	5.7-28.5	1/875-1/350	5-25	1/1000-1/400
3	50-75	1/200-1/50	40-60	1/250-1/63	33-50	1/300-1/75	28.5-43	1/350-1/88	25-37.5	1/400-1/100
4	>75	>1/50	>60	>1/63	>50	>1/75	>43	>1/84	>37.5	>1/100

Table 3. Actions related to the damages and risk categories in the building.

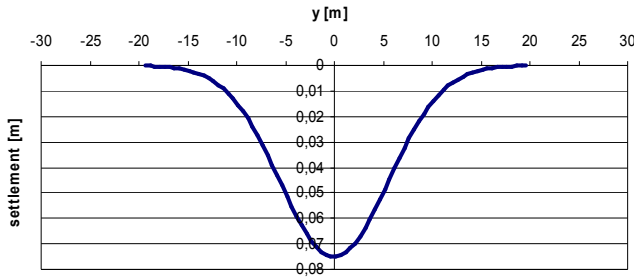| Actions	Description	Risk Category
TYPE A	Special monitoring system and consolidation measures before the passage of the TBM	3-4
TYPE B	Special monitoring system and consolidation measures to be executed before the passage of the TBM in case the monitoring confirms the necessity	2
TYPE C	Buildings that require a light monitoring system and any consolidation measures	1

Figure 4. Typical Gaussian settlement curve.

5. Settlement analysis

In this section, the value of underground commercial center foundation settlement is evaluated based on both empirical and numerical methods for determining the settlement risk level.

5.1 Empirical method

The calculation method is based on empirical observations, widely confirmed by experience and from literature. This method allows evaluating the shape of the subsidence surface induced by excavation in absence of a structure (Greenfield condition).

The settlement curve induced by excavation of a circular tunnel is Gaussian shaped (Figure 4), with maximum settlement value named 'S_{max}' in correspondence of the vertical axis of the tunnel and the area of subsidence equals to the loss volume V_L (extra volume of ground excavated with reference to tunnel excavation value). Many case histories (e.g. Attewell *et al.*, 1982, 1984; New and O'Reilly, 1991) for different geotechnical conditions confirm the effectiveness of this approach.

5.1.1 Formulation

Settlements 's' with reference to the distance from the axis of the tunnel 'y' can be evaluated with the following equation (Attewell *et al.*, 1982):

$$s = s_{max} \cdot e^{\left(\frac{-y^2}{2i^2}\right)} \tag{1}$$

where 'i' represents the distance of the inflection point from the axis, which is the point with a higher angular deformation. For overburden higher than the tunnel diameter 'i' is calculated by Equation (2) (Attewell *et al.*, 1982):

$$i = k \cdot z \tag{2}$$

where 'z' is the vertical level of the tunnel axis and 'k' is depending on the geotechnical characteristics of the ground (Guglielmetti *et al.*, 2008). Settlements are evaluated with reference to the foundation level of the buildings assuming

that the settlement curve is still Gaussian shaped (Mair *et al.*, 1997). The volume of the subsidence curve Vs is equal to (3) (Attewell *et al.*, 1982):

$$V_s = \sqrt{2\pi} \cdot i \cdot s_{max} \cong 2.5 \cdot i \cdot s_{max} \tag{3}$$

So the maximum settlement is:

$$s_{max} = \frac{V_s}{2.5 \cdot i} \tag{4}$$

The method is based on the definition of the percentage of volume loss induced by excavation, and on the assumption that the shape of the settlement curve is depending on the parameter 'k'. V_s is volume of the settlement trough per meter of tunnel advance [m^3/m], defined as a percentage V_L of the unit volume V of the tunnel is equal to (5) (Attewell *et al.*, 1982):

$$V_s = A_{excavation} \cdot V_L \tag{5}$$

where, '$A_{excavation}$' is the excavation area. The volume loss V_L is related to (Guglielmetti *et al.*, 2008):

- loss at the face depending on the displacement of the ground at the face toward the machine,
- gap between the ground and the lining before installation of the ring, i.e. the thickness of the shield,
- deformability and resistance of the ground at the interface with the excavation profile,
- experience and capacity of the specialized personnel,
- alignment: in the curve with low radius the driving operation of the machine can cause additional settlements.

Recent experiences with closed-face mechanized tunneling (EPB and Slurry Shields) have generally shown that in sands and gravels, a high degree of settlement control can be achieved and small volume losses are recorded (i.e. often VL < 0.5%), while in soft clays, VL ranges between 1 and 2%, excluding the long-term settlements. Leblais *et al.* (1995) reported volume losses in the range 0.2-0.9% for 9.25-m diameter tunnels driven through dense, fine Fontainebleau sands at depths ranging from 22 m to 52 m (Leblais *et al.*, 1995).

In this study, the soil type that will be excavated is silty sand and the tunnel diameter and depth of the crown are 9.15 m and 13.1 m, respectively. So the volume loss is considered equal to 1% for these conditions. The key parameters to evaluate the settlement shape, k, V_L and z, are respectively equal to 0.3, 1%, and 17.7m.

5.1.2 Settlement calculation based on empirical method

Calculated settlement values based on the empirical method are summarized in Table 4. In this table, settlement values are presented at the three points under the foundation of commercial structure. Resulted settlement calculation indicates the amount of maximum settlement of commercial structure foundation based on assumed value of 1% for

Table 4. Settlement values based on empirical method.

ID	K	Z(m)	V_L(%)	y(m)	i	A(m^2)	V_s(m^3/m)	S_{max}(mm)	S(mm)
Left corner of foundation	0.3	17.7	1	-13.8	5.31	66.48	0.66	50.08	1.71
Above the tunnel axis	0.3	17.7	1	0	5.31	66.48	0.66	50.08	50.08
Right corner of foundation	0.3	17.7	1	25.11	5.31	66.48	0.66	50.08	7×10^4

volume loss is equal to 50.08 mm.

5.2 Numerical method

Calculation of the underground commercial center foundation due to tunnel excavation with mechanized method by EPB-TBM is done by the PLAXIS finite element software code (Vermeer and Brinkgreve, 1998). Within the PLAXIS code, after the defining the geometry of the problem, assigning geotechnical specifications of the soil layers, segments material, and water table, the settlement calculation and stress-strain analysis are done through two phases by the stage construction capability of the software. Simulating processes, calculation phases, and results are presented as following.

5.2.1 Material specification and water table condition

Based on existing studies in the corridor of the TURL2, soil of the mentioned region is mainly silt with low plasticity (ML) and silty sand (SM) and the water table is located at a depth of 8.8 m. Geotechnical specifications used for soil layers of the model are presented in Table 5. Moreover, a beam element is utilized for modeling the segments and its specifications are presented in Table 6.

5.2.2 Loading

In order to calculate the settlement, the values of loads including the traffic load, underground commercial center weight and the weight of structures close to commercial center are considered in modeling in terms of distributed loads as shown in Table 7.

5.2.3 Settlement calculation based on numerical method

The settlement calculation shows that the maximum amount of commercial center foundation settlement based on the assumed value of 1% volume loss (tunnel contraction) is equal to 46.24 mm. Vertical displacement counters are depicted in Figure 5. According to it, the maximum vertical displacement occurs above the tunnel axis under the commercial structure foundation.

Table 5. Geotechnical specifications used for soil layers of the model.

ID	Material Model	Type	Dry Density (kN/m^3)	Wet Density (kN/m^3)	Permeability (m/day)	Elastic Modulus (kN/m^2)	Poisson Ratio	Cohesion (kN/m^2)	Internal Friction Angle
ML	Mohr-Coulomb	Drained	16.7	20	0.00423	4E04	0.35	17	27
SM	Mohr-Coulomb	Drained	16.4	19.8	0.043	6.5E04	0.3	7	34

Table 6. Specifications of beam elements for modeling of the segments.

ID	Material Model	EA (kN/m)	EI (kN/m^2/m)	d (m)	W (kN/m/m)	Poisson Ratio
0.15	8.4	0.35	1.125E05	1.103E07	Elastic	Segment

Table 7. Amounts of various types of load in the model.

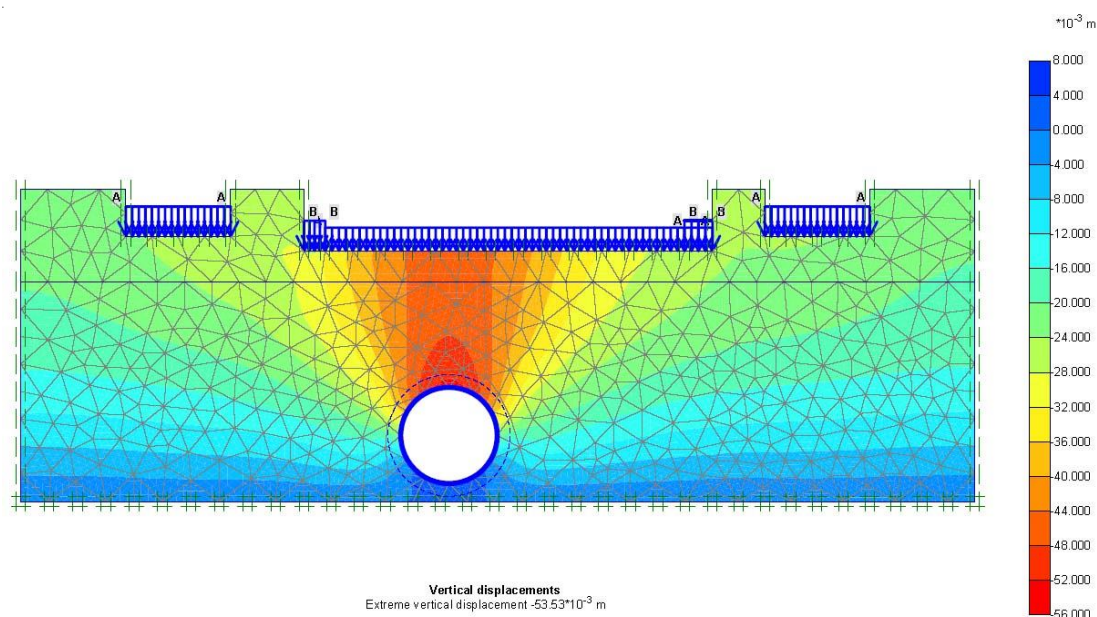| ID	Traffic Load	Underground Commercial Center	Vicinity Houses
Amount (kN/m^2)	20	7	35

Figure 5. Calculated vertical displacement of the underground at the commercial center.

6. Risk category

According to the performed settlement calculations, the maximum values of settlement on the bottom of commercial structure using semi-empirical and numerical methods are 50.08 mm and 46.24 mm, respectively. Hence, the settlement risk categorization of the commercial structure is placed in level 4 by the semi-empirical method and in level 3 by the numerical method based on findings shown in Table 2. Considering the Table 3, the risk category of the building settlement will be type A. So according to the table, any tunneling process in this section needs a special monitoring system and consolidation measures before the passage of the TBM.

7. Conclusions

In this paper, the risk level assessment for settlements of a commercial center foundation located at the Tabriz urban railway line 2 rout is presented. The method of risk level assessment is well defined and the risk level is classified. Then, the value of the underground commercial center structure settlement is estimated using both empirical and numerical methods. Empirical analysis shows that the maximum value of settlement on the bottom of commercial structure is 50.08 mm and the finite element analyses results show that the value of the underground commercial center settlement equals to 46.24 mm. Finally, settlement risk level of the commercial center structure is determined based on presented definitions. The results show that using a semi-empirical method, the settlement risk level due to tunneling falls in the 4th level and based on numerical method in 3rd level. Consequently, risk category of building settlement will be type A

and any tunneling process in this section needs a special monitoring system and consolidation measures before passing the TBM.

References

Attewell, P.B. and Woodman, J.P. 1982. Predicting the dynamics of ground settlement and its derivatives caused by tunneling in soil. Ground Engineering. 15, 13-22.

Attewell, P.B. and Taylor, R.K. 1984. Ground Movements and their Effects on Structures, Chapman and Hall, New York, U.S.A., pp. 132-140.

Boscardin, M.D. and Cording, E.G. 1989. Building response to excavation-induced settlement. Journal of Geotechnical Engineering. 115, 1-21.

Burland, J.B. Broms, J.B. and de Mello, V.F.B. 1977. Behavior of foundations and structures on soft ground. Proceedings of the 9th International Conference on Soil Mechanics and Foundation Engineering (SMFE), Tokyo, Japan, July 10- 15, 1977, 495-546.

Chiriotti, E. Marchionni, V. and Grasso, P. 2000. Porto light metro system, Lines C, S and J. Compendium to the Methodology Report on Building Risk Assessment Related to Tunnel Construction. Normetro – Transmetro. Internal technical report (in Italian and Portuguese)

Clough, G.W. and O'Rourke, T.D. 1990. Construction induced movements of in-situ walls. P. Lambe and L.A. Hansen, Editors. American Society of Civil Engineers (ASCE), Geotechnical Special Publication, Reston, Virginia, U.S.A., pp. 439-470.

Cording, E.J. and Hansmire, W.H. 1975. Displacements around soft ground tunnels. Proceedings of the 5th Pan-Ameri-

can Conference on Soil Mechanics and Foundation Engineering, Buenos Aires, Argentina, October 27-31, 1975, 571-633.

Guglielmetti, V. Grasso, P. Mahtab, A. and Xu, S. 2008. Mechanized Tunneling on Urban Areas – Design methodology and construction control, Taylor & Francis Group, London, U.K., pp. 128-149.

Leblais, Y. Andre, D. Chapeau, C. Dubois, P. Gigan, J.P. Guillaume, J. Leca, E. Pantet, A. and Riondy, G. 1996. Settlements induced by tunneling, Recommendations of Workgroup of French Association of Tunnels and Underground Space (AFTES), Paris, France.

Mair, R.J. Taylor, R.N. and Burland, J.B. 1996. Prediction of ground movements and assessment of risk of building damage due to bored tunneling. Proceedings of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground, Balkema, Rotterdam, Netherlands, 1996, 712-718.

Mair, R.J. and Taylor, R.N. 1997. Bored tunneling in the urban environment. Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering (ICSMFE), Hamburg, Germany, September 6-12, 1997, 2353-2385.

New, B.M. and O'Reilly, M.P. 1991. Tunneling induced ground movements; Predicting their magnitude and effects. Proceedings of the 4th International Conference on Ground Movements and Structures, invited review paper, Cardiff, Pentech Press, London, July 7, 1991, 671-697.

Peck, R.B. 1969. Deep excavations and tunneling in soft ground. Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, State-of-the-art volume, Mexico city, 1969, 225-290.

Rankin, W. J. 1988. Ground movements resulting from urban tunneling: Predictions and effects. Engineering Geology of Underground Movements. 5, 79-92.

Selby, A. R. 1988. Surface movements caused by tunneling in two-layer soil. Engineering Geology of Underground Movements. 5, 71-77.

Vermeer, P.A. and Brinkgreve, R.B.J. 1998. PLAXIS Finite Element Code for Soil and Rock Analysis, Balkema, Rotterdam- Brookfield, Netherlands, pp. 1-114.

Zaw Zaw, A., Dhiraj, K. and Christian S. 2006. Ground movement prediction and building damage risk-assessment for the deep excavations and tunneling works in Bangkok subsoil. Proceedings of the International Symposium on Underground Excavation and Tunneling, Bangkok, Thailand, February 2-4, 2006, 281-297.