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Analysis of a TBM Tunneling Effect on Surface Subsidence: A Case Study from Tehran, Iran

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***Abstract*—**The development and extension of large cities induced a need for shallow tunnel in soft ground of building areas. Estimation of ground settlement caused by the tunnel excavation is important engineering point. In this paper, prediction of surface subsidence caused by tunneling in one section of seventh line of Tehran subway is considered. On the basis of studied geotechnical conditions of the region, tunnel with the length of 26.9km has been excavated applying a mechanized method using an EPB-TBM with a diameter of 9.14m. In this regard, settlement is estimated utilizing both analytical and numerical finite element method. The numerical method shows that the value of settlement in this section is 5cm. Besides, the analytical consequences (Bobet and Loganathan-Polous) are 5.29 and 12.36cm, respectively. According to results of this study, due tosaturation of this section, there are good agreement between Bobet and numerical methods. Therefore, tunneling processes in this section needs a special consolidation measurement and support system before the passage of tunnel boring machine.

***Keywords*—**TBM, Subsidence, Numerical Method, Analytical Method.

I. Introduction

UNDERGROUND transportation systems have been needed in many large cities in the world, notably those interfacing a problem with population and traffic. The tunnels and underground spaces presumably damage the ground, which can cause ground movement and settlement. This matter can be large enough to disrupt the function of nearby structures. Hence, one of the most important issues in tunneling is the safety of construction itself, as well as the nearby structures, especially in urban areas.

There are several methods which are presented by different researchers to estimate surface settlement and displacement. These methods include empirical or semi-empirical methods and many references are presented [1]-[7], or analytical methods [8]-[11].

Bobet [12] presented the general series from stress function in polar coordination as well as he proposed another elastic solution for ground movement of shallow tunnel in saturated ground by developing the solution presented by Einstien and Schawrtz [13] for a deep tunnel in dry ground. In addition to these methods, several practices have been proposed by different researchers to predict surface settlement by numerical methods. Among researchers [14]-[18], Downing [19] analyzed the Heathrow Express Trial Tunnel using imperial college finite element program by adopting untrained properties of London clay. Atzl and Mayer [20] performed a series of FEM analyzes using the modified Cam-clay model to analyze surface and subsurface settlement caused by the Heathrow Express Trial Tunnel. Selby [21] used numerical modeling to study transmission of settlement upwards to the surface in the homogenous medium. Attwell and Woodman [22] proposed the most common available methods for the assessment of Greenfield movement due to tunneling. Zawzaw et al. [23] induced ground movement for the first underground mass transit system project of Bangkok.

In the current research, surface settlement of w_7 section which is located in Sanat square in the route of seventh line of Tehran subway is determined. Settlement calculation of this section by using analytical methods (Bobet and Loganathan-Polous) and numerical methods (Plaxis) finite element software code is estimated. Both of analytical methods which are utilized in this study are appropriate ways to estimate settlement and ground movement for tunneling.

II. Analytical Method

The calculation of surface settlement is based on analytical, widely confirmed by experience and from literature. Analytical methods are based on simplifying assumptions in terms of geometry, ground layering (single homogenous layer), selection of constitutive models and definition of boundary and initial conditions. Scientific literature prepares various analytical formulations [24], [8]-[12]. In the most cases, the authors focused on defining the new stress field generated by the excavation; Fewer works have been devoted the evaluation of distribution of ground movements around the opening and time effects, due to the complexity of such analyses. Among these analytical solutions which are mentioned before, Bobet and Loganathan-Polous methods are utilized to determine surface settlement.

A. The Bobet Method

The solution of shallow tunnel in a saturated ground has been obtained by Bobet [12], with the following assumptions (Fig. 1). (a) circular cross-section with radius r_o; (b) plane strain conditions in direction perpendicular to the cross-section of tunnel; (c) frictionless interface between the ground and

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liner; (d) depth to radius ratio larger than 1.5; (e) homogenous and isotropic ground;(f) poroelastic behavior of the ground and elastic liner; (g) small thickness of the liner(i.e. liner thickness, $t<<r_o$); and (g) permeability of the ground small enough such that no excess pore pressure dissipate during construction(i.e. undrained conditions apply).

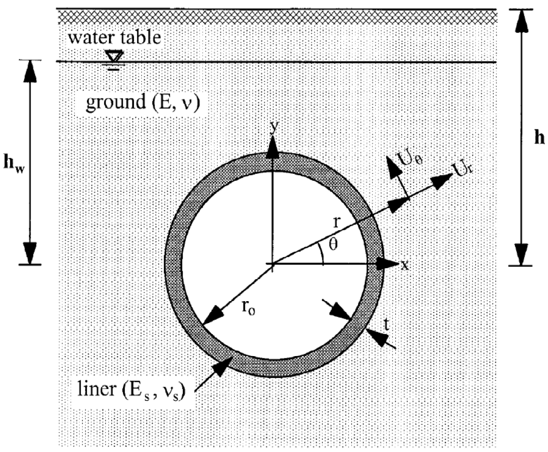

Fig. 1 Shallow tunnel

Of particular interest to this study is the short-term (i.e. immediately after construction) ground movements of shallow tunnel in saturated ground with or without application of air pressure during construction. Hence, calculation of maximum settlement without air pressure, (1) and for a tunnel excavated under air pressure, (2).

$$\delta_{max} = -\frac{wr_0}{h} + \frac{1+\nu}{E}\left\{-\frac{1}{2}\gamma r_0{}^2 1nh + \gamma_b h(1-k) r_0\left[-\frac{r_0}{h} + \frac{3}{4}\left(\frac{r_0}{h}\right)^3 - \frac{1}{4}\left(\frac{r_0}{h}\right)^5\right]\right\}$$

(1)

$$\delta_{max} = -\frac{wr_0}{h} + \frac{1+\nu}{E}\left\{-\frac{1}{2}\left[\gamma r_0^2 1nh + \gamma_b h(3-k) r_0^2\right] + \gamma_b h(1-k) r_0\left[\frac{3}{4}\left(\frac{r_0}{h}\right)^3 - \frac{1}{4}\left(\frac{r_0}{h}\right)^5 + \gamma_w h r\left(\frac{r_0}{h}\right)^2\right]\right\}$$

(2)

In these relations: (w) gap parameter, (r_o) radius of tunnel, (υ) Poisson's ratio,(γ_b) and (γ_w) are the buoyant unit weight of the ground and unit weight of the water, respectively. (E) Young's modulus, (γ) unit weight of the ground, (k)is the coefficient of earth pressure at rest,(h) and (h_w) are the depth of the tunnel below the ground surface and below the water table.

B. The Loganathan-Polous Method

This method represents an improvement over the Verruijt and Booker methods [9], which takes the ground loss into account, considering it uniformly distributed along the tunnel wall but giving it greater value along crown zone. Moreover, Loganathanand-Polous determines the ground-loss value introducing gap parameter [25]. In particular, the equivalent undrained ground loss ε_0 is defined as:

$$\varepsilon_0 = \frac{4gr + g^2}{4R^2} \quad (3)$$

where g is gap parameter and r is the tunnel radius. Finally, the formula proposed by Loganathan-Polous to estimate the surface settlement is expressed as:

$$U_{Z=0} = \frac{H(1-\nu)}{H^2 + X^2}(4gR + g^2)\exp\left[-\frac{1.38x^2}{(H\cot\beta + R)^2}\right] \quad (4)$$

The Fig. 2 shows ground deformation pattern ground tunnel section which is considered by Bobert and Loganathan-polous.

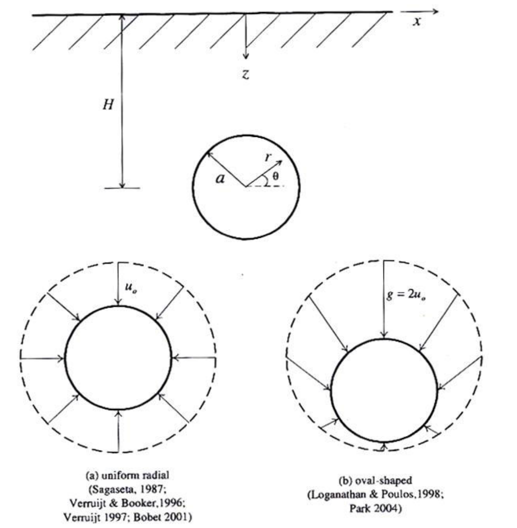

Fig. 2 Ground deformation patterns around the tunnel section

III. CASE STUDY

Tehran is one of the crowded and important cities in north of Iran. Tehran is one of the crowded and important cities in north of Iran. With a 720km^2 spatial size and population of about 12 million considering to political, economical and industrial situation of Tehran, establishing the subway systems to control traffic is unavoidable. Hence, in terms of studies the final plan of subway in Tehran includes 9 lines which show in Fig. 3. The seventh line of Tehran subway with the length of 26.9km is being established to connect the eastern part of the city with western one. The geology of seventh line of Tehran subway is presented in Fig. 4.This route includes 28 stations which all of them have been established underground. The excavation operations of seventh line of Tehran subway, by considering to studies, cross section of tunnel (9.14m), passing through residential regions and limitations for settlement on ground level, have been excavated applying a mechanized method using an EPB-TBM. Technical characteristics of machine are shown in Table I.

Fig. 3 Plan of Tehran subway

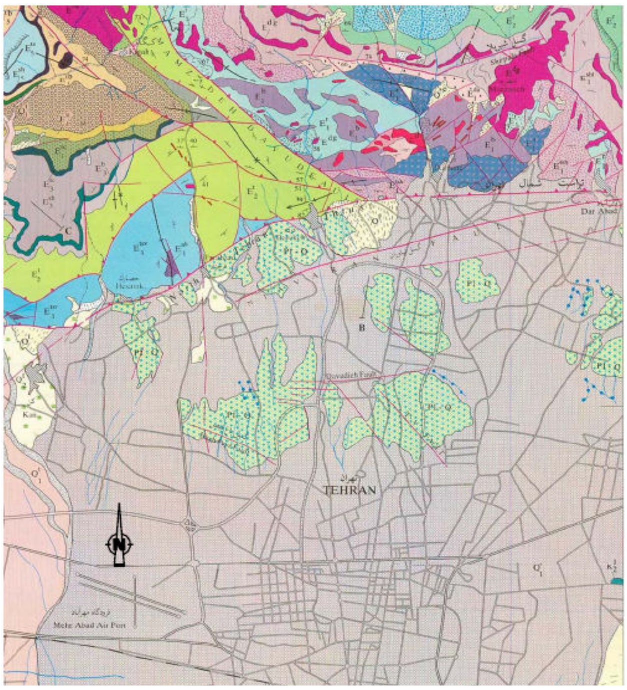

Fig. 4 Geology of seventh line of Tehran subway

TABLE I
TECHNICAL CHARACTERISTICS OF EPB-TBM

Machine kind	Earth pressure balance
Shield diameter(mm)	9150
Shield diameter(mm)	9110
Shield length (m)	9
Total length of machine (m)	110
Machine weight (ton)	1250

TABLE II
GEOTECHNICAL SPECIFICATIONS USED FOR SOIL LAYERS OF THE MODEL

Internal friction angle (degree)	Cohesion (MPa)	Young Module (MPa)	Poisson Ratio	Soil material (BSCS classification)	Soil depth(m)
32.5	29.42	64.74	0.285	CLG/GCL	0-1.7
30	29.42	49.03	0.3	CLG	1.7-4
35	29.42	78.45	0.27	GCL	4-10
32.5	29.42	63.74	0.285	CLG/GCL	10-18
27	39.23	29.42	0.35	CL	18<

TABLE III
CHARACTERISTICS OF SEGMENTS

Density (T/m^3)	Poisson Ratio	UCS (Mpa)	Young Module (Gpa)
2.4	0.15	34.32	22.5

A. Geotechnical Parameters of Soil

In order to evaluate the geotechnical parameters of soil in w_7 section, laboratory studies are utilized. In this section, depth of tunnel and water are 16.1 and 6.6m with the unit weight of dry, total and saturation of soil 16.30, 19, and $20KN/m^3$ respectively. Geotechnical parameters are demonstrated in Table II.

The most important parameter of shields is shield diameter. Outer diameter or in the other word excavation diameter of the seventh line of Tehran subway is 9.14m. In order to support the tunnel segments with the thickness of 35cm are utilized. This cover is used as final support system. Characteristics of segments and support system are shown in Table III.

IV. SETTLEMENT ANALYSIS

A. Analytical Methods

In the both Bobet and Loganathan-Polous method has to compute Gap Parameters**.** The definition of the gap parameter necessarily introduces some on its determination; however; it can be estimated from (5) [26]:

$$w = G_P + U_{3D} + workmanship \tag{5}$$

where $G_p$is the physical gap between the liner and the perimeter of the excavation and includes the thickness of TBM tail skin and the clearance required for erection of the liner; $U_{3D}$is a measurement of the soil movements ahead of the face of tunnel; and the workmanship is a measurement of the overcutting as the TBM is steered.

In this regard, excavation diameter in the seventh line of Tehran subway is 9.14m and outer diameter is 8.99m (segments with the thickness 35cm), thus, the amount of $G_p$in the arch of tunnel is 150mm. In terms of studies which are proposed by Lee and et al. [26] the 3 dimension can be neglected by utilizing proper methods (Earth pressure balance in tunnel face). Hence, this parameter (U_{3D}) is evaluated zero. Besides, by assuming the workers are skilled enough, the ground loss problem can be neglected as well. Therefore, the gap parameter can be determined:

$$w = 150 + 0 + 0 = 150mm \tag{6}$$

The subsidence calculation by using analytical methods (Bobet and Loganathan-Polous) show that the maximum amount of surface settlement is 5.29 and 12.36cm, respectively with assuming gap parameter is 150mm and β= 45°.

B. Numerical Analysis

Calculation of the surface due to tunnel excavation with TBM method is done by the PLAXIS finite element software code. Within the PLAXIS code, after the defining the geometry of the problem, assigning geotechnical specifications of the soil layers, lining material, the subsidence calculation and stress-strain analysis are done through three phases by the stage construction capability of the software. Simulating processes, calculation phases, and results are presented as following.

C. Material Specification

In the tunnel, soil of the mentioned region is Alluvium mainly Gravel and Clay. Geotechnical specifications used for soil layers of the model are presented in Table IV (used Mohr-Coulomb Criterion). Support system includes lattice concrete segments with 0.35m thickness. It specifications is 22,500,000 Kpa as elastic module and $3.66\times10^6$and 3.74×10^4 KN/m as axial stiffness (EA) and bending stiffness (EI), respectively.In order to calculate the subsidence, the values of loads, including the surface weight and traffic load are considered in modeling in terms of distributed loads as 40Kpa in 16m lengths.

TABLE IV
GEOTECHNICAL SPECIFICATIONS USED FOR SOIL LAYERS OF THE MODEL

Type	Elastic Modul e (Kpa)	Poisso n Ratio	Cohesion (Kpa)		Internal Friction Angle		Deep (m)
			Dry	Satura ted	Dry	Satur ated	
Upper Gravel	40,000	0.28	25	20	30	18	4
Gravel andClay	78,45	0.28	29.4	22	30	22	4
Deep Gravel andClay	63,74	0.285	29.4	22.5	27.5	21	27

D. Subsidence Calculation

The subsidence calculation shows that the maximum amount of surface subsidence and crown of tunnel is equal to 5cm and 8.5cm, respectively. Total displacement counters are depicted in Fig. 5. According to it, the maximum displacement of surface occurs the top of tunnel.

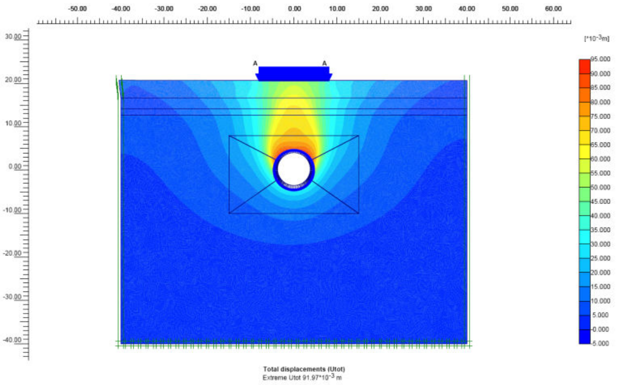

Fig. 5 Calculated total displacement

V. CONCLUSION

The maximum value of surface settlement on the basis of numerical and analytical methods (Bobet and Loganathan-Polous) is displayed. These values are more than critical ones (i.e. 2cm in beneath of streets and 1cm in beneath of structures). Thus, during tunneling suitable campaigns such as: improvement of ground characteristics, structural improvement of buildings and so on should be utilized to reduce of ground settlement. In this section, ground includes different size components, hence, the different consequences between numerical and analytical (Bobrt method) are justified. On the other word, existing of different layers causes to reduce the exactness of analytical method as well. Besides, in comparison with analytical methods results, it can be observed that the Bobet method has good agreement with numerical method (about 5cm in the surface). That is why in order to estimate the value of settlement; Loganathan-Polous method just focuses on geometry of tunnel and Poisson's ratio among the characteristics of the ground and regardless to the effect of water. Whereas, the characteristics of ground and the existence of water has effective influence to occur of settlement on ground. In this regard, neglecting the mentioned factors will be caused the error and incorrect for evaluating the settlement. In general, the proper evaluation of gap parameter is important key to estimate settlement by utilizing experimented analytical method. Also, it can be able to predict the appropriate distribution and intensity of stress.

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