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A novel relationship for predicting the point of inflexion value in the surface settlement curve

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ABSTRACT

Thanks to the technological developments in the tunneling and construction sector, the importance of underground structures is growing rapidly. In this sector, it is essential to protect buildings and other structures from the damage which could be caused by tunnel excavation. In this regard, it is important to predict ground behavior during excavation. So, it is necessary to recognize the nature of surface settlement above these types of grounds. The horizontal distance from the tunnel centerline to the point of inflexion on the surface settlement trough is one of the important parameters in surface settlement prediction. Researchers commonly use various empirical relationships for the estimation of the point of inflexion value. These relationships are not precise for calculating these values. Suggesting an accurate and new relationship requires a comprehensive investigation. Therefore, in this study we used both field and detailed numerical modeling approaches to investigate the effects of different parameters on the point of inflexion value. The selected parameters were the following: cohesion, angle of internal friction, tunnel depth, tunnel diameter, Poisson's ratio, Young's modulus, unit weight, face support pressure, and surface surcharge. Four of the largest tunnel construction projects, namely Istanbul, Tehran, Mashhad and İnönü tunnels were chosen. The three-dimensional finite difference code FLAC3D was used to model all conditions. A new relationship was formulated to estimate the point of inflexion value on the surface settlement trough which might be caused by tunneling excavation including not only Tunnel Boring Machine (TBM) but also other excavation type including New Australian Tunneling Method (NATM). The point of inflexion values obtained from the new equation was found to be in good agreement with the actual results from different case studies.

1. Introduction

There are many geotechnical and geometrical parameters considered as having an impact on the prediction of the exact amount of the horizontal distance from the tunnel centerline to the point of inflexion on the surface settlement trough (i) value. To that end, several methods such as numerical, empirical and field observation methods have been developed to investigate the effects of these parameters. Researchers commonly use numerical modeling methods such as finite element and finite difference analysis in their studies. Although use of numerical modeling and field observation is very helpful, the application of various empirical relationship methods is sometimes more practical, effective and economical. Empirical methods are based on empirical formulas derived from past observations and are mostly limited to some field measurements (Chakeri et al., 2010; Chambon and Corté, 1994; Ercelebi et al., 2011; Glossop, 1978; Martos, 1958; Schmidt, 1969; Attewell and Farmer, 1974; Atkinson and Potts, 1977; O'Reilly and New, 1982; Hamza et al., 1999; Mair, 1983; Herzog, 1985; Arioglu, 1992). The number of parameters used in empirical relationships is quite important in obtaining accurate results. Besides, the number of parameters to be used in empirical methods is restricted. Therefore, proposing new relationships which consider a higher number of effective parameters would certainly yield better results in predicting the point of inflexion value. The selected parameters can be a combination of cohesion, angle of internal friction, tunnel depth, tunnel diameter, Poisson's ratio, Young's modulus, unit weight, and surface surcharge. Suggesting such a relationship requires a comprehensive investigation. Therefore, in this study we used both field and detailed numerical modeling approaches to investigate the effects of different parameters on the point of inflexion. Three-dimensional finite difference (3D-FD) code FLAC3D was used to model all conditions. Finally, a new relationship was formulated to estimate the inflexion point value caused by tunneling excavation. Then the previous empirical results were compared to the results from the new relationship.

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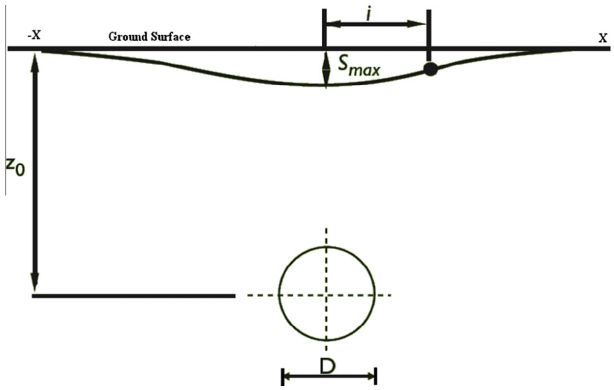

Fig. 1. Surface settlement profile.

2. Empirical methods for point of inflexion estimation

Determination of ground movements during tunnel excavation is a significant matter for most engineers. Peck (1969), Schmidt (1969) investigated surface settlement data from a large number of tunnels and proposed that the Gaussian function as shown in Eq. (1) can be applied for describing the surface settlement trough.

$$S_x = S_{\max} exp\left(-\frac{x^2}{2i^2}\right) \tag{1}$$

where x is the horizontal distance from the tunnel centerline and i is the horizontal distance from the tunnel centerline to the point of inflexion on the surface settlement trough.

According to Fig. 1, the point of inflexion (i) is one of the most effective parameters in describing the nature of surface settlement. There are several suggested methods based on field data for predicting the point of inflexion parameter. Different empirical solutions have been presented by various researchers to calculate the value of point of inflexion (Table 1).

3. Geology of sites

Tunnels with different geotechnical properties were selected for numerical modeling and verification of the new equation. These tunnels are as follows:

- Tehran Metro (Line 7, For numerical modeling).
- Istanbul Metro (Esenler, For verification of new equation).
- İnönü tunnel (For verification of new equation).
- Mashhad Metro (Line 2, For verification of new equation).

Geotechnical properties of each case study are presented as follows:

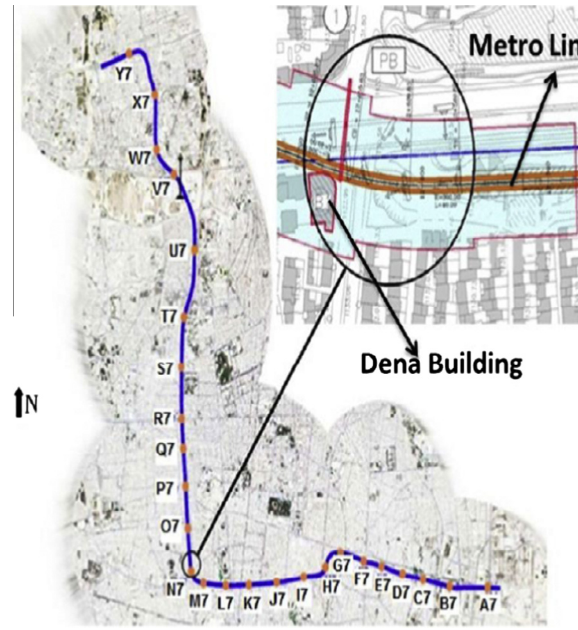

Fig. 2. Main route of Tehran Metro Line 7.

3.1. Tehran Metro (Line 7)

Tehran Metro Line 7 is almost 27 km in length with 26 stations. The Line 7 tunnel can be divided into Lots: one running in East–West Lot has 13 stations, and the other along North–South Lot has 13 stations. Based on this, the drilling work for the two sections starts at Station N7 located at the intersection of Ghazvin Street and Navab Highway using two TBM devices and continues toward the north and the east. In this study, the point of inflexion is investigated for the Line 7 tunnel, South-North Lot, which is to be excavated in the chainage interval of 12 + 600–12 + 710 m between N7 and O7 stations of the Tehran Metro Line. According to the proposed plan the centerlines of Line 7 tunnel in the study area is to be situated 20.8 m below the surface (Fig. 2).

The underground strata in Tehran along the tunnel axis consist of a series of alluvial layers with variable grain size distribution from clay to course gravel with cobbles and erratic blocks. Fig. 3 shows the geological section for this region. In this zone, two boreholes were drilled. In order to establish a geotechnical model for the project area, the soil layers have been grouped into four main categories, regarding the soil classification and geotechnical test results. These grouping results and geotechnical data are presented in Table 2. The geotechnical parameters shown in Table 2 have

Table 1
Empirical formulas predicting the point of inflexion value.

	Researcher	Empirical solution	Explanation
1	Schmidt (1969)	$I = R\left(\frac{Z_0}{2R}\right)^{0.8}$	Clays by shielded machines
2	Attewell and Farmer (1974)	$I = R\left(\frac{Z_0}{2R}\right)$	–
3	Atkinson and Potts (1977)	$i = 0.25(1.5Z_0 + 0.5R)$	Dense sand and OC clay
		$i = 0.25(Z_0 + R)$	Loose sand
4	O'Reilly and New (1982) and Hamza et al. (1999)	$i = 0.43Z_0 + 1.1$	Cohesive soil by shielded mechanics
5	Mair (1983)	$i = 0.5Z_0$	Cohesive soil
6	Herzog (1985)	$i = 0.4Z_0 + 1.92$	All types of soils
7	Leach (1985)*	$i = (0.57 + 0.45Z_0) + 1.01$	
8	Arioglu (1992)	$i = 0.9R\left(\frac{Z_0}{2R}\right)^{0.88}$	All types of soils by shielded machines
		$i = 0.4Z_0 + 0.6$	Clays by shielded machines
		$i = 0.386Z_0 + 2.84$	All types of soils

Where Z_0 is the tunnel depth and R is the tunnel radius.
* It was referred by Chow (1994).