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Technical Note

An estimation of subsurface settlement due to shield tunneling

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A B S T R A C T

An empirical method based on the normal distribution function is proposed to estimate the magnitude and extent of subsurface settlement associated with shield tunneling. Based on field measurement data, empirical relationships are established between surface and subsurface settlement troughs. Assuming the surface settlement due to tunneling could be obtained by the analytical, numerical, or field monitoring method, based on these relationships, the range of subsurface-settlement can be easily estimated. Twenty three sets of measured subsurface settlement profiles associated with tunneling with open, slurry and earth-pressure-balance shields are compared with the predicted curves. It is concluded that the application of normal probability function can be extended to estimate the subsurface settlement due to shield tunneling. The width of the subsurface settlement trough decreases with increasing depth, and the maximum subsurface settlement increases with increasing depth. The subsurface settlement curves calculated using the proposed method are in fairly good agreement with field measurements for various types of shield machines, depths and diameters.

1. Introduction

The construction of every soft-ground tunnel is associated with a change in the state of stress in the ground, and with corresponding strains and displacements. If these quantities become excessive, they may damage adjacent and overlaying facilities. In fact, many shield tunnels are driven through areas where structures and underground pipelines already existed. Therefore, generally it is required that the construction of tunnels should not excessively damage nearby buildings, streets and utilities.

The area under the surface of urban streets and sidewalks is filled with public utilities, such as storm drain, sewer, steam, water, gas pipes, and electrical and telephone ducts. Based on the field monitored data due to shield tunneling, Cording and Hansmire (1975) reported that the maximum subsurface settlement was greater than the maximum surface-settlement, and the width of the subsurface settlement trough was narrower. As a result, the subsurface utilities above the tunnel probably would experience a larger angular distortion than surface facilities. This is the main reason why the magnitude and extent of subsurface-settlement should be carefully investigated by the design engineer.

O'Reilly and New (1982) suggested that the subsurface settlement trough due to tunneling can be described by the normal probability function. Based on centrifuge test results, Mair et al. (1993) studied the location of the inflection point, and the maximum subsidence of the subsurface settlement trough. It was concluded that both the surface and subsurface settlement troughs could be approximated by the normal probability curve. Park (2004) used the elastic solutions to estimate the tunneling-induced ground deformations in soft ground. Surface and subsurface settlements from five case studies were compared with the proposed analytical solutions, and good agreement of the predicted and monitored ground deformations were seen for tunnels in uniform soft clay. In this note, an empirical estimation of subsurface settlement based on field measured settlement data is proposed, which provides a simple and practical alternative to analytical and numerical solutions.

In this study, it is proposed that the subsurface settlement trough can be properly described with the normal distribution function. Based on field measurement data, empirical relationships are established between surface and subsurface settlement troughs. Assuming the surface settlement due to tunneling could be obtained by either the analytical, numerical, or field monitoring method, based on these empirical relationships, the range of subsurface-settlement can be easily estimated. At the end of this note, twenty three sets of measured subsurface settlement profiles are compared with the predicted curves.

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2. Normal probability settlement curve

Based on field data, Peck (1969) suggested that the surface settlement trough over a single tunnel can usually be approximated by the error function or normal probability curve as follows:

$$S_{(s,y)} = S_{max,s} \cdot \exp\left(-\frac{y^2}{2i_s^2}\right) \quad (1)$$

where $S_{(s,y)}$ is the surface settlement at offset distance y from the tunnel center line, $S_{max,s}$ is the maximum surface settlement above the tunnel center line, and i_s is the distance from the inflection point of the trough to the tunnel center line as illustrated in Fig. 1. The parameter i_s is commonly used to represent the width of the surface settlement trough. In Fig. 1, R is the radius of the tunnel, T is the thickness of overburden, and Z_o is the center-line depth of the tunnel.

O'Reilly and New (1982) and Mair et al. (1993) suggested that the subsurface settlement due to shield tunneling could also be described with the normal probability curve. As a result, the subsurface settlement trough at the depth z is approximated as follows:

$$S_{(z,y)} = S_{max,z} \cdot \exp\left(-\frac{y^2}{2i_z^2}\right) \quad (2)$$

where $S_{(z,y)}$ is the subsurface settlement at offset distance y from the tunnel center line, $S_{max,z}$ is the maximum subsurface settlement above the tunnel center line, and i_z is the distance from the inflection point of the trough to the tunnel center line as illustrated in Fig. 1.

2.1. Settlement trough parameters i and S_{max}

The surface settlement data monitored during the excavation of Mexico City Central Interceptor Tunnel reported by Schmitter et al. (1981) are plotted in Fig. 1. For this case, the tunnel was constructed by an open shield with a diameter $2R = 3.5$ m, where R was the radius of the tunnel. The center line of the tunnel was located at the depth Z_o of 23.5 m and the soil excavated was silty clay, as indicated in case No. 9 of Table 1.

By applying natural logarithm on both sides of Eq. (1), the following relationship can be obtained.

$$\ln S_{(s,y)} = \ln S_{max,s} + \left(\frac{-1}{2i_s^2}\right)y^2 \quad (3)$$

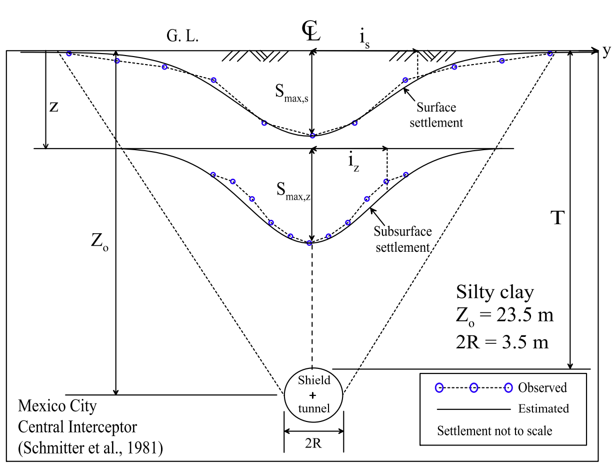

Fig. 1. Modeling of surface and subsurface settlement with normal distribution curves.

Eq. (3) is a slope-intercept linear equation in two variables ln $S_{(s,y)}$ and y^2, where $\left(\frac{-1}{2i_s^2}\right)$ is the slope and ln $S_{max,s}$ is the intercept. If the measured settlement data are plotted in a figure with ln $S_{(s,y)}$ as the vertical coordinate and y^2 as the horizontal coordinate, a straight line can be regressed. From the slope of the straight line, the width parameter $i_s = 17.7$ m of the surface settlement trough can be determined. It may be observed in Fig. 1 that the measured surface settlement data are in fairly good agreement with the estimated curve based on the normal probability model for $i_s = 17.7$ m and $S_{max,s} = 122$ mm.

The subsurface settlements measured at the depth $z = 6.0$ m for the Mexico City Central Interceptor project are also plotted in Fig. 1. With the procedure mentioned above, the width parameter $i_z = 12.3$ m for the subsurface settlement trough are determined. In the figure, the measured subsurface data are in fairly good agreement with the curve calculated with the normal distribution function for $i_z = 12.3$ m and $S_{max,z} = 140$ mm. It should be mentioned that, to expose the research subject, the settlement value and the tunnel depth in Fig. 1 are not indicated with the same scale.

3. Relationship between surface and subsurface settlement troughs

Based on 24 sets of surface and subsurface settlement due to shield tunneling monitored in the United Kingdom, United States, Ireland, Japan, Canada, Mexico, Taiwan, China, and Thailand, Table 1 has been summarized chronologically. In this table, the location of the case, ground conditions encountered, type of shield machine used, tunnel depth, tunnel diameter, settlement-trough width parameter i and maximum settlement S_{max} obtained with the normal probability method and the related reference are listed. In Table 1, the maximum subsurface settlement varies from only 7 mm in Case 1, up to 333 mm in Case 4 and 336 mm in Case 10.

It may be observed in Table 1 that, in the literature published before 1981, most tunnels were driven with the hand-excavated or mechanical open-type shields. After 1990, most cases of soft ground tunneling listed in Table 1 were driven with more advanced close-type shields, such as earth-pressure-balance (EPB) and slurry shields.

3.1. Surface and subsurface trough width

The relationship between the surface and subsurface settlement-trough width-parameters (i_s and i_z) has been established in this study. The data listed in Table 1 are plotted in Fig. 2, with the dimensionless i_z/i_s ratio as the horizontal coordinate and the normalized depth z/T as vertical coordinate. In the figure, all data points are located in a narrow zone between the upper and lower bound curves. It is clear that the width of the subsurface settlement trough decreases with increasing depth. This observation is in good agreement with the research finding of Cording and Hansmire (1975), Mair (1979), and O'Reilly and New (1982). It should be noted that Fig. 2 provides a quantified relationship between surface and subsurface settlement trough widths.

3.2. Surface and subsurface maximum settlement

Based on the maximum settlement values listed in Table 1, Fig. 3 is prepared with the dimensionless $S_{max,z}/S_{max,s}$ ratio as the horizontal coordinate, and the normalized depth z/T as the vertical coordinate. The $S_{max,z}$ and $S_{max,s}$ data was actually measured in the field. In this figure, the subsurface maximum settlement $S_{max,z}$ increases with increasing depth. This observation is also in agreement with the conclusions reported by Cording and Hansmire (1975), Mair (1979), and O'Reilly and New (1982). With this empir-