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Technical Note

An estimation of subsurface settlement due to shield tunneling

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ABSTRACT

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.

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

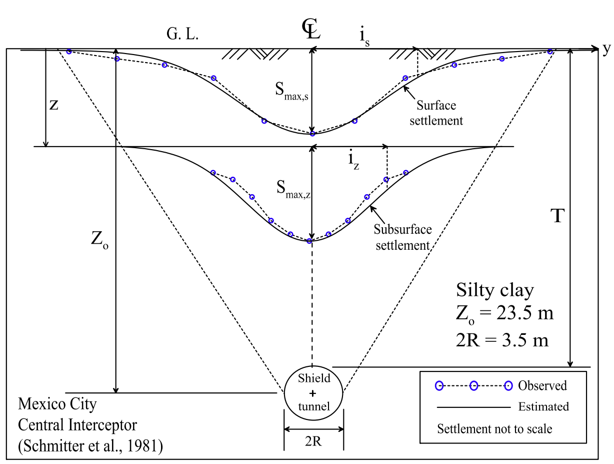

Fig. 1. Modeling of surface and subsurface settlement with normal distribution curves.

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-

Table 1
Cases of shield tunneling and related surface and subsurface settlement trough width parameter and maximum settlement.

Case No.	Case location	Ground condition	Shield type	Tunnel depth Z_0 (m)	Tunnel diameter $2R$ (m)	Depth z (m)	Width parameter i_z (m)	Maximum settlement $S_{max,z}$ (mm)	Reference
1	London Transport Fleet Line, Green PK, y1, U.K.	Clay	Hand-excavated shield	29.3	4.146	0.0	N/A	6.0	Attewell and Farmer (1974)
						9.5		7.0	
						15.4		8.0	
						22.0		10.0	
						25.2		11.0	
						27.1		15.0	
2	London Transport Fleet Line, Green PK, z1, U.K.	Clay	Hand-excavated shield	29.3	4.146	0.0	N/A	6.0	Attewell and Farmer (1974)
						8.5		7.7	
						14.9		8.0	
						20.9		8.0	
						26.5		15.0	
3	N.W.A Sewerage Scheme Tyneside, Hubburn, U.K.	Clay	N/A	7.50	2.01	0.0	4.6	8.0	Attewell et al. (1975)
						2.6	3.8	10.0	
						4.0	3.4	11.0	
						5.22	3.0	12.0	
4	Washington Metro A-2, Line c, U.S.A.	Silt sand & silt clay	Mechanical shield	14.6	6.40	0.0	5.9	150.0	Cording and Hansmire (1975)
						2.32	4.7	207.0	
						10.8	2.4	333.0	
5	Belfast Sewerage Scheme, Ireland	Organic silt	Hand-excavated shield	4.55	2.70	0.0	3.08	N/A	Glossop and Farmer (1977)
						0.9	2.4		
						1.6	2.3		
6	Japan Subway, Case B-2	Soft cohesive soil	Mechanical shield	27.5	7.06	0.0	N/A	67.0	Hanya (1977)
						10.3		76.0	
						20.4		118.0	
7	N.W.A. Sewerage Tyneside, Willington Quay Siphon, U.K.	Silt alluvial clay	Hand-excavated shield	13.37	4.25	0.0	8.0	65.0	Attewell et al. (1978)
						2.75	6.2	70.0	
						8.0	4.1	81.0	
8	Thunder Bay Sanitary Trunk Sewerage Array 2, Canada	Clay	Full-face boring machine	10.5	2.47	0.0	3.4	52.0	Palmer and Belshaw (1980)
						4.5	2.2	59.0	
						6.0	1.8	69.0	
9	Mexico City Central Interceptor	Silty clay	Open shield	23.5	3.5	0.0	17.7	122.0	Schmitter et al. (1981)
						6.0	12.3	140.0	
						12.0	11.2	150.0	
10	Taipei Sewerage Sec. 1, Taiwan	Clay	EPB shield	9.0	4.00	0.0	4.1	204.0	Fang and Chen (1990)
						2.9	3.0	277.0	
						6.0	2.5	336.0	
11	Taipei Sewerage Sec. 2, Taiwan	Silt clay & silt sand	Slurry shield	14.4	4.83	0.0	9.4	N/A	Fang and Chen (1990)
						3.5	6.8		
						9.6	5.1		
12	Taipei Ell-Chorng Flood Way, Taiwan	Silty clay	Slurry shield	12.0	4.83	0.0	9.9	144.0	Lee et al. (1990)
						5.0	4.6	138.0	
						11.0	4.3	121.0	
13	Milwaukee Sewer, Section CT-8-1, U.S.A	Silty clay	EPB shield	16.0	3.20	0.0	N/A	69.0	Ilsley et al. (1991)
						13.3	4.6	98.0	
14	Milwaukee Sewer, Section NS-10-U, U.S.A	Organic clay	Slurry shield	7.94	2.25	0.0	N/A	22.0	Ilsley et al. (1991)
						6.0		47.0	
15	Milwaukee Sewer, Section CT-7, U.S.A	Organic clay	EPB shield	7.44	3.57	0.0	N/A	19.0	Ilsley et al. (1991)
						4.9		27.0	
16	Taipei MRT, Lot CH218, Taiwan	Silty clay	EPB shield	12.5	6.00	0.0	N/A	9.0	Chang (1993)
						4.6		10.8	
						7.7		12.6	
						8.7		14.7	

(*continued on next page*)

Table 1 (*continued*)

Case No.	Case location	Ground condition	Shield type	Tunnel depth Z_0 (m)	Tunnel diameter $2R$ (m)	Depth z (m)	Width parameter i_z (m)	Maximum settlement $S_{max,z}$ (mm)	Reference
17	London Bank Station, U.K.	London clay	EPB shield	41.0	7.8	0.0	11.2	11.0	Mair et al. (1993)
						5.3	9.8	11.0	
						25.7	5.2	19.0	
						33.3	3.7	32.0	
18	Furongjiang Sewer Tunnel, China	Clay	EPB shield	5.6	4.2	0.0	3.18	76.0	Yi et al. (1993)
						0.91	2.5	77.0	
						1.8	2.3	74.0	
						2.5	N/A	74.0	
19	Japan	Clay	N/A	16.9	3.63	0.0	4.6	6.0	Toombs (1995)
						4.3	3.6	8.0	
						6.1	3.2	9.0	
						9.1	2.5	10.0	
						12.3	1.8	16.0	
20	Taipei MRT CH218, B1 RE33, Taiwan	Clay	EPB shield	18.5	6.0	0.0	8.9	20.0	Moh et al. (1996)
						10.0	5.9	27.0	
21	Mexico Sewerage System, Line A	Soft clay	Slurry shield	13.0	4.00	0.0	9.8	25.0	Romo (1997)
						5.0	6.8	18.0	
						10.15	3.7	28.0	
22	Mexico Sewerage System, Line B	Soft clay	Slurry shield	13.0	4.00	0.0	10.0	31.0	Romo (1997)
						5.0	6.9	24.0	
						10.15	3.8	36.0	
23	Bangkok Sewer Tunnel, Thailand	Soft to stiff clay	EPB shield	18.5	2.66	0.0	4.62	5.0	Park (2004)
						2.0	4.97	12.0	
						4.0	4.49	14.0	
						6.0	3.96	16.0	
						8.0	3.5	18.0	
						10.0	3.05	22.0	
						12.0	2.62	25.0	
						14.0	2.09	35.0	
24	Hangzhou Metro, Right Line, China	Silty clay	EPB shield	19.0	6.20	0.0	10.43	12.0	Chen et al. (2011)
						3.0	9.71	16.0	
						7.0	9.62	24.0	

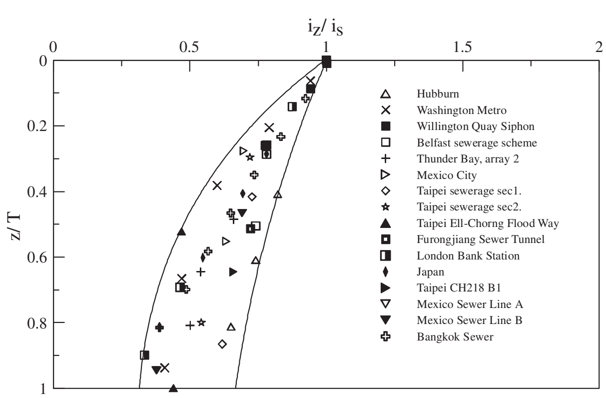

Fig. 2. Subsurface and surface settlement width parameter ratio i_z/i_s with depth.

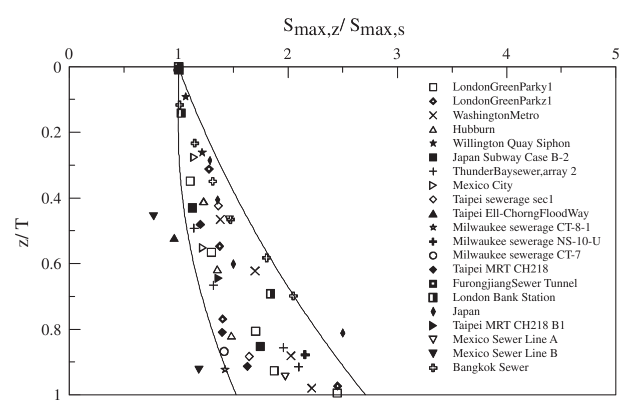

Fig. 3. Subsurface to surface maximum settlement ratio $S_{max,z}/S_{max,s}$ with depth.

ical relationship, if the maximum surface settlement $S_{max,s}$ due to shield tunneling is known, the range of maximum subsurface settlement $S_{max,z}$ can be rationally estimated.

3.3. Illustrative example

If the surface settlement due to shield tunneling is known, the surface settlement parameters i_s and $S_{max,s}$ can be estimated with Eq. (3). By applying the subsurface parameters i_z and $S_{max,z}$ obtained from Figs. 2 and 3 to the normal probability Eq. (2), the range of subsurface settlement curve at any depth above the tunnel can be estimated. An illustrative example is provided here to demonstrate how to analyze the problem with the proposed method.

For the N.W.A. Sewerage Scheme at Tyneside, Hubburn, United Kingdom (Case No. 3 in Table 1), a tunnel with diameter $2R = 2.01$ m, center-line depth $Z_o = 7.5$ m (thickness of overburden $T = 6.5$ m) was driven through clayey soils. With measured surface settlement data and Eq. (3), the surface-settlement width-parameter $i_s = 4.6$ m can be determined. The maximum surface settlement $S_{max,s} = 8.0$ mm was measured above the center-line of the tunnel.

To estimate the subsurface settlement at the depth of 2.6 m, the dimensionless depth $z/T = 0.4$ is needed. In Figs. 2 and 3, corresponding to $z/T = 0.4$, the range of surface to subsurface width-parameter ratio i_z/i_s varies from 0.60 to 0.82, and the maximum settlement ratio $S_{max,z}/S_{max,s}$ varies between 1.13 and 1.43. At the depth of 2.6 m, the range of subsurface parameters would be $i_z = 2.76–3.77$ m and $S_{max,z} = 9.0–11.4$ mm. By applying the estimated $(i_z)_{low} = 2.76$ m and $(S_{max,z})_{low} = 9.0$ mm to Eq. (2), the small subsurface settlement trough can be obtained. The large subsurface settlement profile can be evaluated by applying

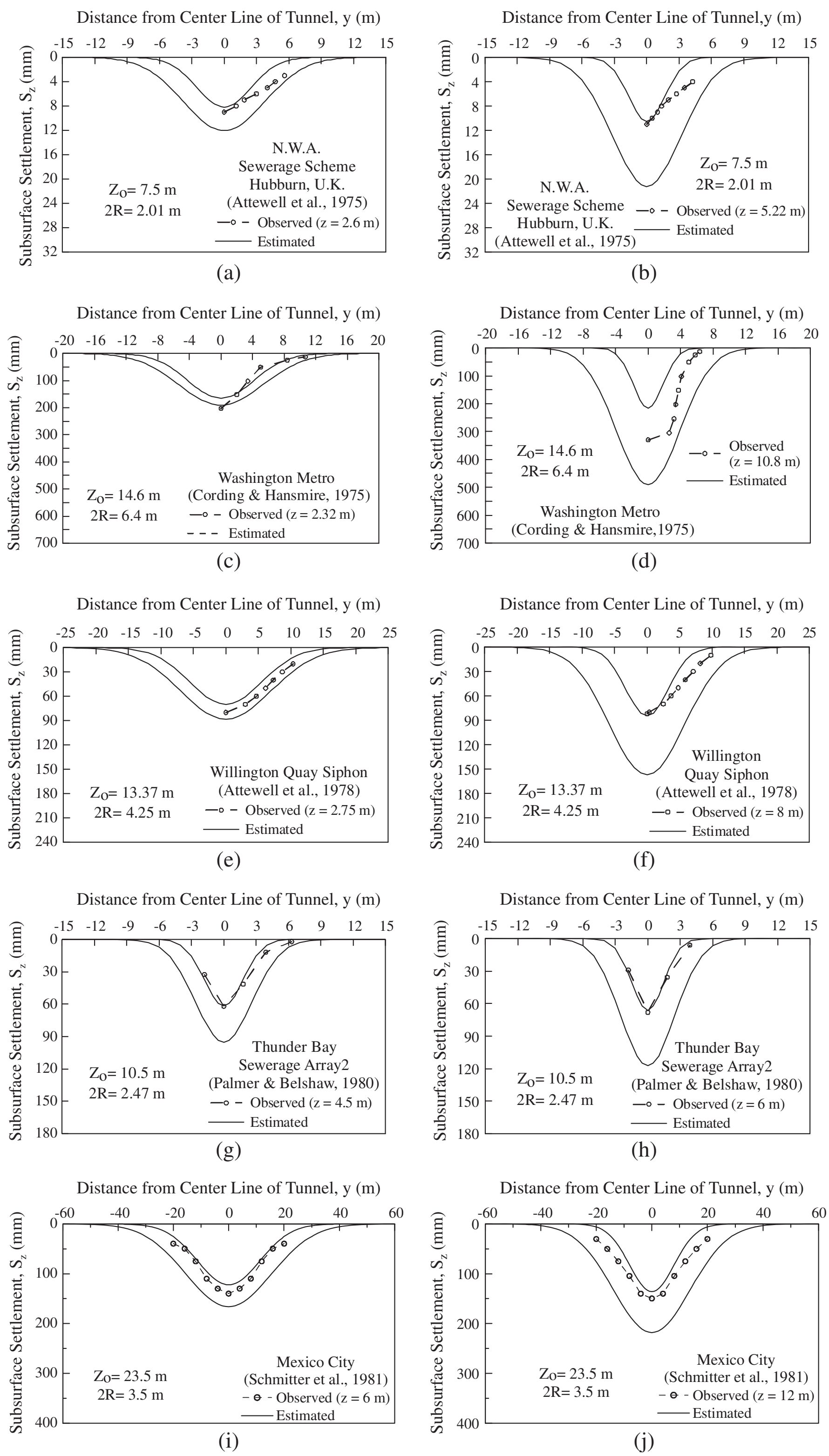

Fig. 4. Measured subsurface settlement vs. estimated curves for tunnels excavated with open shields.

$(i_z)_{high}$ = 3.77 m and $(S_{max,z})_{high}$ = 11.4 mm to the error function, as shown in Fig. 4(a). It is clear from this figure that measured subsurface settlement data are properly bounded by the estimated small and large subsurface settlement curves. However, at this stage, the proposed method remains doubtful, unless it can be effectively backed up by large amounts of field measurements.

4. Empirical estimation of subsurface settlement

In this section, 23 measured subsurface settlement profiles associated with shield tunneling have been collected and classified according to the type of shield machine used. These profiles are compared with estimated subsurface subsidence troughs.

4.1. Subsurface settlement due to open shield tunneling

In Fig. 4(a)–(j), ten subsurface settlement profiles due to tunneling with open shield machines are evaluated. While the tunneling for Washington Metro was executed in silty-sand and silty-clay layers, all other cases were conducted in clayey soils. Fig. 4(e) and (f) shows the subsurface settlements measured for the tunneling of Willington Quay Siphon in the United Kingdom. For this case, the tunnel diameter was 4.25 m and the center-line depth was 13.37 m (Attewell et al., 1978), and an open-shield was used. To balance the groundwater pressure at the face, excavation was carried out with the compressed-air pressure of 90 kN/m^2.

Fig. 4(e) shows, at 149 days after the face passed the settlement point, the measured subsurface subsidence data are located between the estimated small and large curves. It should be mentioned that the subsidence data indicated in this note are long-term settlements. In Fig. 4(a)–(j), most of the field data are within the estimated range. It should be noted that part of the data listed in Table 1 are illustrated in Figs. 2 and 3, but not in Fig. 4 because of insufficient field data.

4.2. Subsurface settlement due to slurry shield tunneling

In Fig. 5(a)–(f), six subsurface settlement profiles due to tunneling with slurry shields are illustrated. Fig. 5(c)–(f) shows the field data measured for the tunneling of sewer line A and B in Mexico City. Romo (1997) reported the tunnel diameter was 4.0 m, the center-line depth was 13.0 m, and a slurry shield was selected for tunneling. Soil samples obtained during site investigation and cone penetration test results indicated the soils to be excavated were extremely-soft clayey deposits. As a result, field monitoring arrays including surface markers, extensometers and inclinometers were established to control the surface and subsurface ground movements.

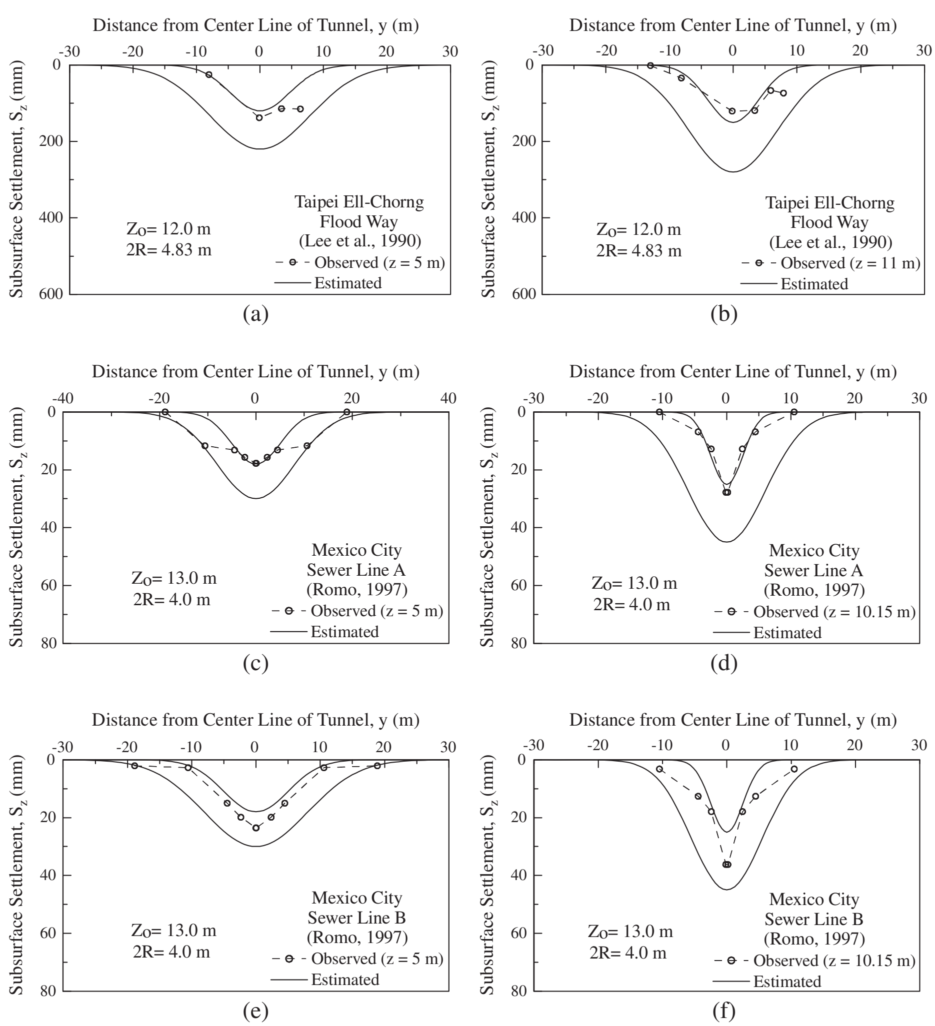

Fig. 5. Measured subsurface settlement vs. estimated curves for tunnels excavated with slurry shields.

Fig. 5(c) shows, at the depth of 5.0 m, the maximum subsurface settlement above the centerline of sewer line A is slightly less than the expected value. The subsurface settlement profile is somewhat flat. In Fig. 5(d), at the depth of 10.15 m, the measured data is close to the estimated small subsurface-settlement curve. It is clear in Figs. (a) to (f) that most of the field data are in fairly good agreement with the predicted range.

4.3. Subsurface settlement due to EPB shield tunneling

In Fig. 6(a)–(g), seven subsurface settlement profiles due to tunneling with EPB shields are indicated. Fig. 6(b)–(d) shows the field data measured for the tunneling of Furongjiang sewer main in Shanghi, China. Yi et al. (1993) reported the tunnel diameter was 4.2 m; the center-line depth was only 5.6 m, as indicated in case No. 18 in Table 1. Excavation was carried out in saturated soft clay below groundwater table. The thickness of overburden was quite thin (T = 3.5 m), which was less than the tunnel diameter D. The disturbance of soils due to excavation might induce large amount of ground movements above the shallow tunnel. Therefore, the contractor established monitoring arrays including surface markers, extensometers and pore pressure transducers. Maximum subsurface subsidence measured at the depth of 0.91, 1.8 and 2.5 m was 77, 74, and 74 mm, respectively. In Fig. 6(b)–(d), the data measured above the shallow sewer tunnel are in fairly good agreement with the curves calculated with error function. It can be observed in Fig. 6(a)–(e) that most of the field data is within the estimated range. It should be noted that the empirical relationships shown

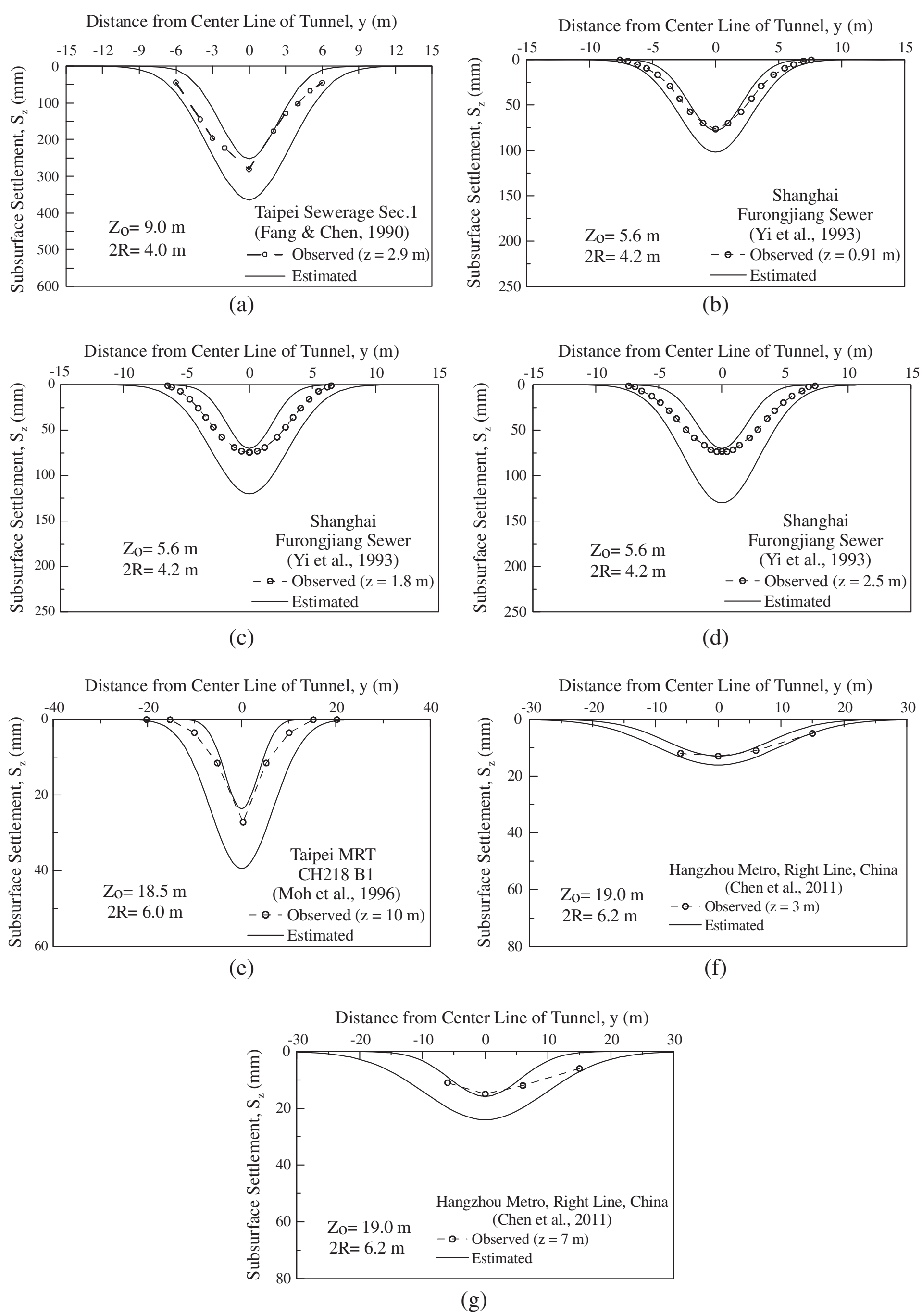

Fig. 6. Measured subsurface settlement vs. estimated curves for tunnels excavated with EPB shields.

in Figs. 2 and 3 are actually based on the field data shown in Figs. 4–6. Therefore it is not surprising that the predicted curves are in good agreement with the field data.

It should be mentioned that the emphasis of this technical note is to establish the empirical relationship indicated in Figs. 2 and 3. The field data shown in Figs. 4–6 is used to obtain the correlation in Figs. 2 and 3. The monitored data is also used to illustrate the applicability of the normal probability function to estimate the subsurface settlement trough due to shield tunneling.

The subsurface settlements due to EPB shield tunneling for the Hangzhou Metro in China reported by Chen et al. (2011) are indicated in Fig. 6(f) and (g). The more recent field information in these figures is intentionally excluded from Figs. 2 and 3. Based on the surface settlement data and the empirical relationship shown in Figs. 2 and 3, the estimated subsurface settlement profiles at the depths $z = 3$ and 7 m are found to be in fairly good agreement with the field monitored data. It is obvious that more reliable information should be compiled regarding subsurface settlement due to shield tunneling in future studies.

Based on the 23 sets of data illustrated in Figs. 4–6, it can be concluded that the subsurface subsidence trough can be properly described by the proposed empirical method. The application of normal probability function can be used to estimate the subsurface settlement troughs due to shield tunneling with open, slurry and EPB shields.

5. Advantages and limitations

Since the method proposed is empirical, to apply this method properly, a civil engineer should be fully aware of its advantages and limitations. The advantages of the proposed method are briefly listed as follows:

(1) *Reliability* – The method proposed is based on field data collected from actual tunneling cases. At different depths, the estimated curves are found reliable when compared with field measurements reported from different parts of the world.
(2) *Simplicity* – By inputting basic data and surface settlements concerning tunneling, the subsurface settlements can be determined rapidly. Because no complicated computing facility is required, this method is especially beneficial for a preliminary estimation of subsurface subsidence. The outcomes obtained can be used for comparison with results from numerical analysis.
(3) *Flexibility* – With the rapid technical development of shield machines and construction methods, the S_{max} and i values would be effectively reduced with time. The proposed table and figures can be modified and kept up to date.

The major limitations of the proposed method are listed as follows:

(1) The prediction of subsurface subsidence totally depends on an accurate estimation of surface settlement data.
(2) Important factors related to the quality of construction (such as backfill grouting operation, amount of overcut) cannot be rationally evaluated.
(3) Only the subsurface settlement due to tunneling can be estimated. Other important information, such as lateral ground movement and pore-pressure variation around the tunnel cannot be determined.
(4) Sousa et al. (2011) reported, for tunneling in tropical residual clays with highly porous structure, the induced surface settlements can be larger than crown-level settlements along a tunnel axis. In grounds where substantial contraction takes place upon shearing or drainage, the subsurface settlements may tend to decrease with depth. In this special type of ground, the proposed procedure cannot be applied.

6. Conclusions

In this note, a simple empirical method based on the normal distribution function and the subsurface to surface $S_{max,z}/S_{max,s}$ and i_z/i_s relationships is proposed to estimate the subsurface ground movement. It is found that the application of normal probability function can be extended to estimate the subsurface settlement troughs due to shield tunneling. Field measurements indicate that the width of the subsurface settlement trough decreases with increasing depth, and the subsurface maximum settlement increases with increasing depth.

In this study, 23 measured subsurface settlement profiles associated with shield tunneling are collected and compared with estimated subsurface subsidence troughs. It is found that 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. However, the method proposed is empirical, to apply it properly, engineers should be fully aware of the advantages and limitations of this method.

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