Building deformations, induced by shallow service tunnel construction and protective measures for reducing of its influence

Déformations de bâtiments induites par la construction d'un tunnel de service peu profond et actions de protection pour réduire son influence

Ilyichev V.A.
Russian Academy of Architecture and Construction Sciences, Moscow, Russia

Nikiforova N.S.
Moscow State University of CivilEngineering, Moscow, Russia

Tupikov M.M.
Company Ltd 'Podzemproekt', Moscow, Russia

ABSTRACT: Results are cited for theoretical and experimental investigations of the prediction of deformations of the ground surface and buildings, which develop during the opening of shallow utility tunnels constructed by the shielded method, and also measures taken to reduce the deformations that occur as a consequence of such an opening.

RÉSUMÉ : Cet article est consacré à la recherche théorique et expérimentale, concernant la prévision des déformations de la surface du sol et des bâtiments qui surviennent à la pose de galeries techniques peu profondes construites au tunnelier à bouclier. Des mesures pour réduire ces déformations sont aussi proposées.

KEYWORDS: Surface and building settlement, shallow service tunnel, loss of ground, empirical method for settlements predicting.

1 INTRODUCTION

The method outlined by Peck (1969) for analysis of ground-surface settlement demonstrates its dependence on the distance to the axis of the tunnel, *D* and *H*, characteristics of the soil (considering the stratification of the soils), and the excess-soil factor V_L. Burland et al. (2001) have developed a method in which a formula is given for the argument of the inflection point on the curve of the function of ground-surface settlements during the opening of a tunnel. Excavations (Clough G.W. and Schmidt 1981), which have modified the Peck method, supplementing it with a moisture-content characteristic, have also come into use. Figure 1 shows a surface-settlement diagram based on the empirical methods cited with parameters entering as component parts of the formulas.

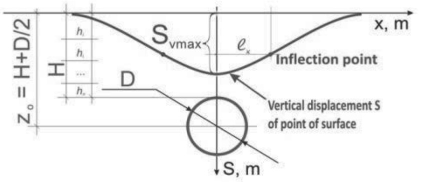

Figure 1. Surface-settlement diagram for opening tunnel

Construction practice demonstrates that methods employed to calculate settlement for deep tunnels are not always applicable for shallow tunnels. In contrast to deep transportation tunnels, the diameter of utility tunnels *D* = 3-4 m, the depth of embedment *H* = 4-8 m, and the relative depth of embedment $\chi = H/D$ does not exceed 3.

2 METHOD FOR PREDICTION OF SURFACE SETTLEMENT DURING OPENING OF SHALLOW TUNNELS

To substantiate prediction of surface deformations during the opening of shallow tunnels, a series of projects were subjected to in-situ settlement measurements, which were then compared with data acquired by empirical methods for deep tunnels (Table 1).

Figure 2 shows the 4-m-diameter storm-drain collector along the Gruzinskii Street line in Moscow, which is being constructed by the shielded method by a Lovat RME 163 SE series 23300 tunneling unit with a soil surcharge. The depth of embedment was 4.0-8.0 m (the analyses were performed by the N. M. Gersevanov Scientific-Research Institute of Foundations and Underground Structures, and scientific accompaniment by the Scientific-Research Institute of Foundations and Structures and the ANO ANCA RAACS).

Figure 2.Service tunnel construction on Gruzinsky Val Str.In Moscow.

A characteristic feature was that the shield passed close to the surface in the filllayer of soil. The Lovat Company had predicted V_L= 1.78%, but measurements indicated V_L = 5.5%; this was higher than the value for deep tunnels. Due to the shallow depth and small cross section of the tunnels, the distribution of in-situ pressure over the height of the face should vary considerably with distance from the surface ~(2-3)*D* (where D is the diameter of the tunnel). The effective counter pressure that can be developed over the height of the face may therefore be insufficient at the bottom of the face, and excessive at the top. This is confirmed by a discharge of foam onto the surface at two points along the route of the tunnel on the Gruzinskii Street line.

Table 1. Shallow service tunnels in Moscow, settlements due to its construction were used for method of surface settlements predictions.

Project	Geologic-engineeringconditions	V_L, %	H, m	D, m	$\chi = H/D$
Storm drain collector for Gruzinskii Street line. Station No. 1	0.5 m of fill sands; up to 12 m sands ranging from silty to coarse, loose sands of medium density, and saturated sands; groundwater table at 2-4 m	2.6	4.0	4	1
Storm-drain collector on Gruzinskii Street line. Station No. 4	0.5 m of fill sands; up to 12 m sands ranging from silty to coarse, loose sands of medium fineness, and saturated sands; groundwater table at 2 m	4.3	4.5	4	1.13
Collector at Il'inskaya substation. Section 1	2 m of medium-fine sand with construction debris; 1 m of sand of medium fineness; up to 8 m of silty, semi-hard, medium density, moist and saturated clay; groundwater table at 3 m	5	5.4	3.2	1.69
Novobratts evo-Voikovskay a collector. Section between chamber Nos. 5-7	3 m of fill sands; 2 m of highly plastic clays; then fine sands; groundwater table at 1.5-4 m	1.1	6.0	3.5	1.71
Collector from Ugresha substation. Section No. 4	0.5 m of fill, and sand to lowest bed of formation in region analyzed; up to 12 m of alluvial and fluvioglacial sands of medium fineness, coarse and gravelly sands, moist and saturated sands, silty and fine sands, and moist sands of medium density; groundwater table at 3 m	5	5.5	3.2	1.72
Collector from Ugresha substation. Section No. 3	1.30 m of fill, and sand to lowest bed of formation of region ana-lyzed; up to 10 m alluvial and fluvioglacial sands of medium fineness, coarse and gravelly sands, moist and saturated sands, silty and fine sands, and moist sands of medium fineness; groundwater table at 3 m	5	5.8	3.2	1.80
Collector from Ugresha substation. Section No. 2	2.5 m of fill, and sand to lowest bed of region analyzed; up to 10 m of modern alluvial, fine clayey and silty, saturated sands of medium density; groundwater table at 3 m	5	6.1	3.2	1.90
Collector at Il'inskaya substation. Section 3	2 m of sand of medium fineness with construction debris; 3.8 m of silty, semi-hard clay; up to 8 m of moist and saturated sand of medium fineness and medium density; groundwater table at 2.5 m	5	7.4	3.2	2.31
Collector from Ugresha substation. Section No. 5	4.60 m of fill, 0.7 m of peat, and sand to lowest bed of formation in region analyzed; up to 10 m of alluvial and fluvioglacial sands, coarse and gravelly sands, moist and saturated sands, silty and fine sands, and moist sands of medium fineness; groundwater table at 3 m	5	7.4	3.2	2.31
Novobratse vo-Voikovskay a collector. Section between chambers No. 10-13	1.5-2 m of fill sands; 3-4 m of sands of medium fineness; water table at 4-5 m	2.2	7	3	2.33
Collector from Zolotarev-skaya substation. Section 5	6.3 m of fill layer composed of sandy-loam/clayey-loam soils; 1.4 m of silty, highly plastic clayey loam; up to 4.6 m fine sand of medium density; groundwater table at 3 m	3	8.1	3.2	2.53
Collector from Zolotarev-skaya substation. Section 1	1.5 m of fill layer composed of sandy-loam/clayey-loam soils; 1.5 m of silty, slightly plastic clayey loam; 4 m of sandy, highly plastic clayey loam; groundwater table at 3-4 m	2	5.4	3.2	1.68

According to experimental data acquired during construction of the utility tunnels, the coefficients V_L decrease with increasing H/D. If the sheet piling passes close to the fill layer, or proceeds into it, V_L increases. For the hydrogeologic conditions, the lower the groundwater table (GWT), the lower V_L.

In developing a method for settlement prediction, approximations were obtained for ground-surface settlements on five projects. The confidence coefficient of the approximation R^2 = 0.92-0.99. The coefficients before the parameters in the formulas were established for each section [1]. Based on the correction factors of the approximations, their dependencies on the relative depth of embedment in the form of a second-degree polynomial are obtained by the method of least squares:

$$C_1(\chi) = 1{,}525 - 1{,}147 \cdot \chi + 0{,}353 \cdot \chi^2;$$
$$C_2(\chi) = 1{,}23 - 0{,}871 \cdot \chi + 0{,}212 \cdot \chi^2 \quad (1)$$

Using the correction factors, we developed a method for prediction of surface deformations during the construction of shallow utility tunnels, which is represented by the following formula for ground-surface settlements

$$S_v(x) = C_1(\chi) \cdot S_{vmax} \times e^{-\frac{C_2(\chi) \cdot x^2}{2 l_x^2}} \quad (2)$$

where $S_{v\max}$ is the maximum surface settlement (along the axis of the tunnel), x is the distance from the axis of the tunnel along the horizontal, and l_x is the argument of the inflection point on the settlement curve. S and l are parameters obtained in accordance with the method of Peck (1969) and others.

The correction factors are varied from 1 to 2.5 relative embedment depths of the shallow tunnel.

3 GROUND-SURFACE SETTLEMENTS IN MOSCOW

Soils of different origin and age reside in the Moscow area. Analysis of cores taken by the Mosgorgeotrest has made it possible to isolate seven typical geologic-engineering sections in the area (Moscow City Building Code 2-07-97).

Average physico-mechanical characteristics of the soils in the sections described were presented (Ilyichev et al 2009).

Settlement (a), relative nonuniformity (b), and surface-curvature (c) plots of seven characteristic geologic-engineering sections of Moscow were constructed (using the method of surface-settlement prediction) (Fig. 4) for analysis of surface deformations.

Maximum surface settlements (5-120 mm) and the width of the zone of influence B_{zi}(where it is necessary to conduct geotechnical monitoring) were determined as a function of the depth $z_0$of the longitudinal axis of the tunnel (Table 2).

Table 2.Width of the zone of influence B_{zi}.

Types of geologic-engineering conditions	½ Bzi
I	2.0z0
II	1.5z0
III	1.5z0
IV	2.5z0
V	1.5z0
VI	2.5z0
VII	1.2z0

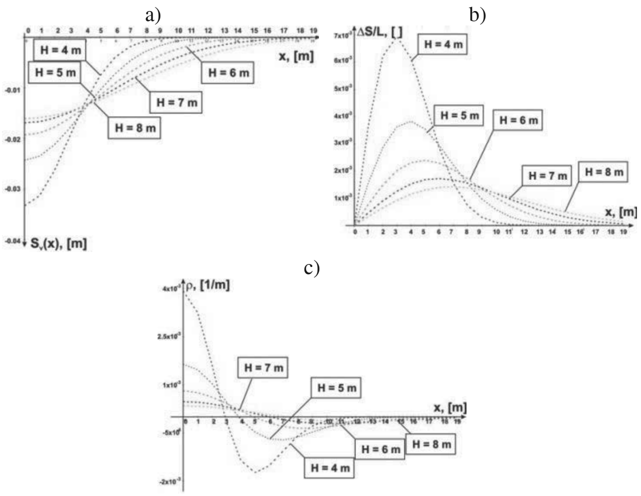

Figure 4.Plots showing settlement (a), relative nonuniformity of surface settlement (b), and surface curvature (c) during opening of shallow utility tunnels for first type of geologic-engineering conditions in Moscow (D = 4 m; V_L = 2%): 1-5) H = 4-8 m, respectively.

4 PREDICTION OF BUILDING SETTLEMENTS DURING OPENING OF SHALLOW TUNNELS

To calculate the settlements of buildings during the opening of a shallow utility tunnel, it is necessary to determine the weight of the building, its stiffness, the distance from the apex of the utility tunnel, the depth and diameter of the tunnel, and the deformability of the soil. For this purpose, we have solved the problem of a beam on an elastic Winkler bed with an assigned support-line displacement, which is described by the formula for vertical displacement based on the method of surface-settlement prediction of a soil.

A building situated transversally in plan to the route of the utility tunnel was modeled by a beam of infinite (the building is situated above the route of the tunnel) and semi-infinite length (the building is situated at a certain distance along the surface of the ground from the axis of the tunnel, Fig. 5). Nikiforova(2008) has proposed and taken a similar approach to prediction of building deformations within the zone of influence of deep trenches.

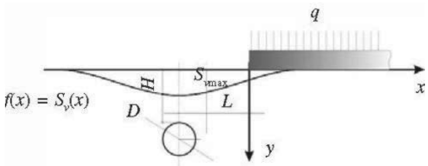

Figure 5.Mutual position of beam of semi-infinite length, and shallow utility tunnel with assigned support-line displacement $f(x)$.

The differential equation of the beam's deflections

$$EJ\frac{d^4y(x)}{dx^4}+k\cdot y(x)=q(x)+k\cdot f(x) \quad (3)$$

whereEJ is the bending stiffness of the beam, k is the coefficient of subgrade reaction of the bed, $q(x)$ is the load on the beam, and $f(x)$ is the assigned displacement of the lines of the beam's elastic support.

B. G. Korenev's (1954) method can be employed to solve the problem of a beam on an elastic bed under an arbitrarily distributed load using an influence function for the displacement of the beam due to a concentrated force.

The boundary conditions of the semi-infinite beam loaded by a concentrated force P on the left end:

$$-EJ\frac{d^3y}{dx^3}\Big|_{x=0}=-P,\ -EJ\frac{d^2y}{dx^2}\Big|_{x=0}=0,\ y(x)\big|_{x=\infty}=0,$$
$$-EJ\frac{dy}{dx}\Big|_{x=\infty}=0,\ -EJ\frac{d^2y}{dx^2}\Big|_{x=\infty}=0,\ -EJ\frac{d^3y}{dx^3}\Big|_{x=\infty}=0 \quad (4)$$

In formula (3), $f(x)$ is the vertical displacement of the surface in accordance with the method of predicting surface settlement during construction of shallow utility tunnels

$$f(x)=S_v(x)=C_1(\chi)\cdot S_{v\max}\times e^{-\frac{C_2(\chi)\cdot x^2}{2l_x^2}}, \quad (5)$$

whereC_1 and C_2 are coefficients, as defined by formulas (1), $S_{v\max}$ is the maximum vertical displacement, and l_x is the distance to the inflection point on the surface-settlement diagram.

According to Korenev(1954), solution of the bending problem for infinite and semi-infinite beams assumes the form, respectively:

$$y_{II}(x)=\frac{P}{2\lambda^3EJ}\cdot e^{-\lambda x}\cdot cos\lambda x, \quad (6)$$

where $\lambda=\sqrt[4]{k/4EJ}$.

Let us rewrite (6) as

$$y(x)=P\cdot K_i(x) \quad (7)$$

where$K_i(x)$ is the line of influence of the load Pon the deflection of the beam.

For an arbitrary load $p(\xi)$, the expression for the deflections

$$y(x)=\int_0^\infty p(\xi)\cdot K_i(x-\xi)d\xi, \quad (8)$$

In the case where beam deflections are caused by the construction of a shallow utility tunnel, expression (8) will take on the form of (9) for a semi-infinite beam

$$y_{II}(x)=\int_0^\infty k\cdot f(x+L)\cdot K_i(x-\xi)d\xi, \quad (9)$$

Thus, the problem of the beam's deflection reduces to calculation of integrals (9).

The expressions derived for the deflections of the infinite and semi-infinite beams assume the forms, respectively

$$y_{II}(x)=\frac{k\cdot\alpha}{4\lambda^3EJ}\cdot e^{-\lambda x-\lambda L}\cdot\frac{\sqrt{\pi}}{\sqrt{\beta}}\cdot(cos\left(\lambda L-\frac{1}{2\beta}\lambda^2+\lambda x\right)- \\ -(a\,cos(\lambda L-\frac{1}{2\beta}\lambda^2+\lambda x)-b\,sin(\lambda L-\frac{1}{2\beta}\lambda^2+\lambda x))) \tag{10}$$

The settlements of buildings of extended length, which are situated at a certain distance from the axis of the tunnel are, respectively

$$S_{II}(x)=(\delta_{II}\cdot\gamma_{II}(x)+\frac{q}{k}) \tag{11}$$

The parameters of formula (11) are:

$\alpha=C_1\cdot S_{v\,max}$, $\beta=C_2/2l_x^{\,2}$, $\lambda=\sqrt[4]{k/4EJ}$, $A_1=1/8\lambda^3EJ$,

$A_2=1/2\lambda^3EJ$, $\delta_{II}=(\sqrt{\pi}/(2\cdot\sqrt{\beta}))\cdot k\cdot\alpha\cdot A_2$,

$N_{II}(x)=\lambda x+\lambda L-(\lambda^2/2\beta)$,

$$\gamma_{II}(x)=e^{-\lambda(x+L)}\cdot(cos(N_{II}(x))- \\ -(a\,cos(N_{II}(x))-b\,sin(N_{II}(x))))$$

where*a*and *b*are parameters for which we have compiled tables of values as a function of L, β, and λ.

Similar results were obtainedfor an infinitebeam, that is, for the building above thetunnel.

The values of *EJ*for buildings with a different number of stories can be determined from recommendation ofFranzius and Addenbrooke(2002), and used for determination of the influence exerted by the weight and stiffness of the building on the settlement of the surface above the tunnel. Here, an *n*-story building will consist of *n*+1 coverings.

The coefficient of subgrade reaction *k*is $(0.3\text{-}0.9)\cdot10^4$ when $E<10$; $(1\text{-}2.9)\cdot10^4$ when $E=10\text{-}20$; and $(3\text{-}8)\cdot10^4$ kN/m^3 when $E=21\text{-}35$ MPa (Uhov et al. 1994).

Let us examine the single-story brick building of rectangular planform at No. 31 Gruzinskii Street (Fig. 6).The utility tunnel with D=4.0 m is being constructed by a Lovat RME 163 SE tunneling unit. In the section under consideration, H=3.0 m, and the load on the foundation q= 26 kN/m^2. Plots of the building's settlements, which were obtained by numerical modeling via the PLAXIS 2D program in the plane statement using a Coulomb-Mohr model, field data, and data determined from formula (11) are presented in Fig. 6, b.

a) b)

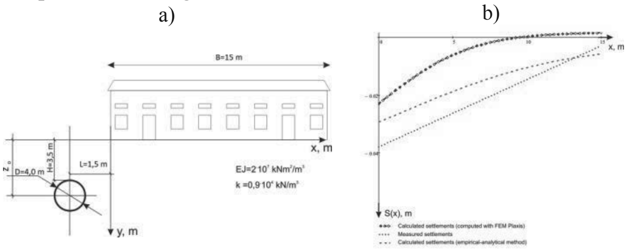

Figure 6. Diagram showing building and tunnel (a); building-settlement plots (b): 1) computed settlements (PLAXIS method); 2) computed deflections of beam (experimental-analytical method); 3) measured settlements.

5 MEASURES FOR MODERNIZATION OF PROCEDURE FOR OPENING SHALLOW TUNNELS

Different methods are employed to reduce the influence exerted by the opening of tunnels on building settlements: installation of cut-off walls, strengthening of the beds and foundations, and also the superstructures of the buildings, compensation injection, etc. In soils comprised of silty, saturated sands, however, chemical stabilization above the tunnel does not always yield positive results (for example, the collector along the Gruzinskii Street line). Strengthening of the foundations with piles is not always possible.

In addition to the existing protective measures, we are proposing measures for modernization of opening procedures, which are directed toward reduction of ground-surface and building settlements. They include modification of the properties of the grout injected into the space behind the lining; reduction of the construction clearance that develops as the shield is advanced; and, continuous pumping of the mixture in the space behind the lining as the shield advances.

Implementation of these measures on the construction project for the collector along the Gruzinskii Street line has resulted in a settlement reduction of up to seven times.

6 CONCLUSIONS

Rules are established for ground-surface deformation during the opening of shallow utility tunnels.

Plots are presented for ground-surface deformations under the geologic-engineering conditions of Moscow. The work zone is defined in accordance with geotechnical monitoring.

A method is developed for prediction of building settlements during the opening of shallow utility tunnels on the basis of analytical solution of the problem of a beam on a Winkler bed with an assigned support-lines displacement describing the vertical displacements of the ground surface.

Formulas for determination of the settlements of the ground surface and building during construction of shallow utility tunnels can be used when H/D = 1-2.5.

Measures for modernization of the opening procedure, the implementation of which has led to a seven-fold reduction in settlements on a project, are proposed.

The investigations conducted were based on Recommendations (2007) (the work was performed by order of the publicly owned joint-stock company Mosinzhproekt).

7 REFERENCES

PeckR.B. 1969.Deep excavation and tunneling in soft ground.State-of-the-art report.*Proceedings of the Seventh International Conference on Soil Mechanics and Foundation Engineering*, Mexico City, pp. 147-150.

Burland J.B., Standing J.R., and Jardine F.M. 2001.Building Response to Tunneling. *Case Studies from Construction of the Jubilee Line Extension*, *London*, Vol. **1**: Projects and Methods, Imperial College, SIRIA, London, United Kingdom.

Clough G.W. and SchmidtB. 1981. Design and performance of excavations and tunnels in soft clay, *Soft Clay Engineering*, edited by E. W. Brand and R. Brenner, 569-634.

Moscow City Building Code 2-07-97, *Beds, Foundations, and Underground Structures* [in Russian], Moscow Government, Moscow (1998).

N. S. Nikiforova 2008. Laws governing bed deformation of buildings near deep trenches, and protective measures.*Author's abstract of dissertation for Doctor of Technical Sciences*, Moscow.

Ilyichev V.A., Konovalov P.A., Nikiforova N.S., Tupikov M.M. 2009 Prediction of surface deformations, caused by shallow service tunnels construction activities in Moscow. *Proc 17th International Conference on Soil Mechanics and Geotechnical Engineering (17th ICSMGE)*.-Egypt, Alexandria, 1993-1996.

Korenev B.G. 1954. *Analysis of Beams and Plates on an Elastic Bed* [in Russian], Gosstroiizdat, Moscow.

Franzius J.N. and Addenbrooke T.I. 2002. The influence of building weight on the relative stiffness method of predicting tunneling-induced building deformation, *Proceedings of the Third International Symposium (IS-Toulouse 2002) "Geotechnical Aspects of Underground Construction in Soft Ground," First Session: Design Methods of Tunnels: Stability, Settlements, and Tunnel Lining*s, Tolouse, France, 23-25 October 2002, 53-57.