Prediction of surface deformations, caused by shallow service tunnels construction activities in Moscow

Les previsions des deformations de la surface a la construction des collecteurs peu profonds a Moscou

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ABSTRACT
In recent years Moscow has seen construction of shallow (up to 8.0 m deep) service 3-4 m dia tunnels for major underground complexes and renovation of existing tunnel networks. In order to preserve the existing buildings, utility lines, pedestrian walks and roads prediction of surface deformations is required.

Seven most typical geological profiles, based on data from Mosgorgeotrest (1998) and from V.A. Ilyichev, P.A. Konovalov and N.S. Nikoforova (2004), have been presented for preliminary prediction of ground deformations.

Correction coefficients to the available empirical surface settlements method for predicting settlements, caused by large-diameter deep (Metro) tunnels, proposed by Peck, R. B. (1969), Burland J.B., Standing J.R. and Jardine F.M. , (2001), have been proposed based on field survey and numeric simulation modeling.

For shallow (up to 8.0 m deep) 3-4 m dia service tunnels correction coefficients have been found.

RÉSUMÉ
Ces dernières années à Moscou on construit des tunnels de communication à une petite profondeur pour de grands ensembles souterrains et la reconstruction des réseaux existants. Les tunnels de diamètre de 3 à 4 м sont construits à la profondeur de 8,0 м au maximum de la surface. Le problème de la garantie de l'intégrité des bâtiments existants et des constructions, des communications, des passages cloutés et des chemins détermine la nécessité de la prévision des déformations de la surface. Sept coupes les plus caractéristiques géologiques, fondées sur les données de Mosgorgeotrest rédigées par V.A.Il'ichev (1998) et P.A.Konovalov et N.S.Nikiforova (2004), peuvent être utilisées pour la prévision préalable des déformations du sol. Les coefficients corrigeant pour la méthode existante empirique de la prévision des déformations, fondés sur les tunnels profonds d'un grand diamètre (le métro), proposes par Peck, R.B. (1969), Burland J.B., Standing J.R. and Jardine F.M. (2001), étaient proposés à la base des essais champêtres et du modelage par les programmes de comptes. Étaient trouvés les coefficients corrigeants pour les tunnels de communication le diamètre de 3 à 4 m d'une profondeur de 8 m au maximum.

Keywords: surface settlement, shallow service tunnel, loss of ground, correction coefficients, empirical method for predicting settlements

1 INTRODUCTION

In recent years Moscow has seen construction of shallow service tunnels (collectors) for major underground complexes. 3-4 m dia tunnels are constructed at 8.0 m depth below the surface (Figure 1). Service tunnels have been mined for two traffic tunnels of the 3rd Transport Ring segment from Lefortovo to Malaya Pochtovaya Str. and Yauza River embankment. Storm water sewage tunnel is being constructed now on Gruzinsky Val Str. for multi-functional underground complex at Tverskaya Zastava Str. traffic intersection. Besides, existing downtown networks are being renovated by shield tunneling, and tunnel networks are being constructed in new development areas (e.g. Voykovskaya-Novobratsevo collector, etc.).

Shallow service tunnels are constructed in congested urban areas, therefore, it is necessary to protect existing buildings and service lines. In order to assign the respective geotechnical monitoring coverage zone it is necessary to assess the extension of tunnel construction operations impact zone.

Deformations of surface and those of nearby structures, caused by tunneling, were studied experimentally by monitoring surface deformations and numerically, e.g. by finite elements method. The obtained values were compared. The results were published in proceedings of international geotechnical conferences (Mexico 1969… Madrid, 2007).

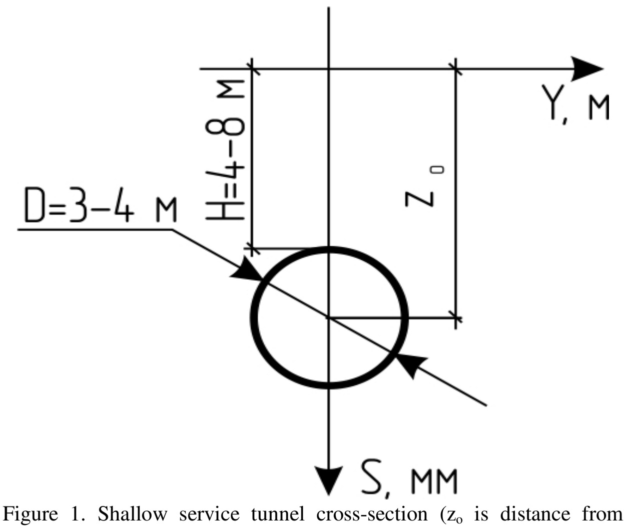

Figure 1. Shallow service tunnel cross-section (z_o is distance from surface to tunnel axis, D is tunnel diameter, H is distance from surface to tunnel top).

Peck (1969), Burland et al. (2001) and other international authors, having analyzed deep large-size traffic tunnels to obtain the values of surface deformations, caused by tunneling,

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elaborated an equation to calculate the surface deformations above the tunnel. Surface vertical and horizontal displacement profiles are shown on Figure 2.

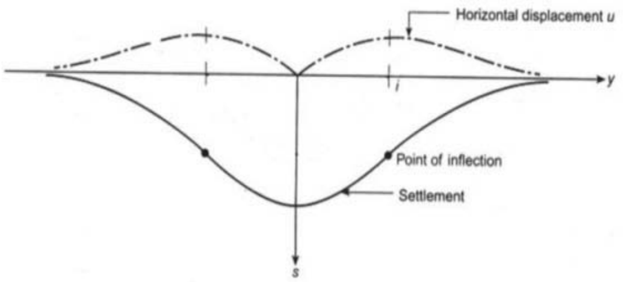

Figure 2. Profiles of surface settlements and horizontal movements above a tunnel, Burland et al. (2001).

Equation of surface settlements above tunnel

$$S_v = S_{v\max} \times e^{-\frac{y^2}{2i^2}}, \quad (1)$$

with S_{vmax} as maximum surface settlement above tunnel axis; y as horizontal distance from tunnel axis; i as coordinate of y settlement curve inflexion point.

The coordinate of the inflexion point on the surface settlement profile above the tunnel is determined for homogeneous grounds i.e., bedded with soil of the same type:

$$i = K \cdot z_0, \quad (2)$$

with K as parameter, depending on soil type (K = 0,2…0,3 for cohesionless soils; K = 0,4…0,5 for stiff clays; K = 0,7 for soft plastic and liquid plastic clays); z_0 as distance from surface to tunnel axis.

Surface maximum settlement $S_{v\ max}$ is calculated with the help of the following formula:

$$S_{v\max} = (0.313 \cdot V_L \cdot D^2 / i), \quad (3)$$

with V_L as relative volume of soil loss in tunneling (soil overcutting ratio) is determined as ratio of surface settlement area V_s over tunnel cross-section area; D as tunnel diameter.

Burland et al. (2001) gave the following equation for surface horizontal displacement:

$$U = S_v \cdot y / z_0, \quad (4)$$

Rechitsky (2005) developed nomograms for quick-look evaluation of surface settlements, based on investigations of deep traffic tunnels construction in Lefortovo and Serebryany Bor in Moscow.

Shallow service tunnels are constructed in heterogeneous soils in Moscow. Construction conditions are distinct in that technogeneous low-strength soft soil is in proximity to the service tunnel.

2 GEOTECHNICAL CONDITIONS IN MOSCOW

Geotechnical profiles of newly developed and downtown areas, elaborated by Moscow Geodetic Center (Mosgorgeotrest) were the basis of most typical profiles for Moscow (Ilyichev et al., 2004) that can be used at preliminary design stages. They are given in Table 1, while their locations are shown on schematic map on Figure 3.

Table 1. Types of most typical geotechnical profiles in Moscow

Type	Soil type, layer thickness, h, m	c, kPa	φ, deg	E, MPa
I	Technogeneous (filled), h_1=1…3	1	10	-
	Clays and clay loams semi-stiff and Clays and clay loams semi-stiff and low plasticity, h_2›10	50	17	30
II	Technogeneous (filled), h_1= 2	1	10	-
	Fine sands, medium density, h_2= 2	2	33	33
	Clay loams, h_3= 2	39	19	26
	Fine and medium density sands h_4›10	1	35	35
III	Technogeneous (filled), h_1=1…2 (2,5)	1	10	-
	Coarse-grained to fine, dense and medium density sands, h_2›10	1	30	27
IV	Technogeneous (filled) h_1= 3	1	10	-
	Clays and clay loams soft plastic and liquid plastic, h_2= 4	37	15	10
	Silty sands, medium density and dense, h_3 ≤5	3	26	20
V	Technogeneous (filled), h_1= 1	1	10	-
	Clays semi-stiff and low plasticity, h_2= 5	65	17	22
	Fine and silty sands, medium density and dense, h_3›10	5	35	30
VI	Technogeneous (filled), h_1= 3	1	10	-
	Clays and clay loams Liquid plastic and liquid (potential organic content), h_2›10	15	15	8
VII	Technogeneous (filled), h_1= 3	1	10	-
	Sands fine and silty, loose, h_2›10	2	26	11

Note: The Table gives mean values of soil physical and chemical parameters.

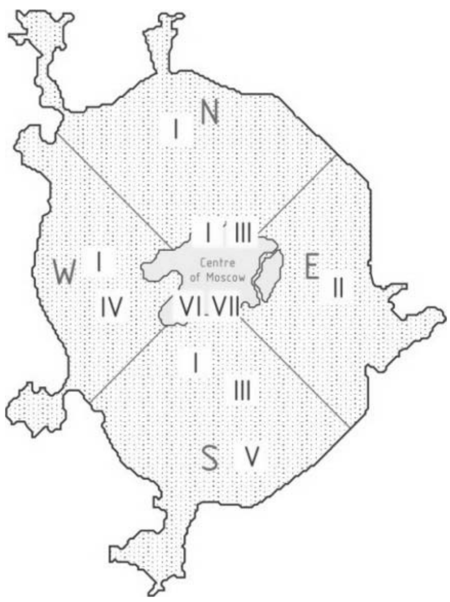

Figure 3. Map of Moscow, showing typical geotechnical profiles (N as north, S as south, E as east, W as west).

3 FORCAST OF SURFACE DEFORMATIONS BY EMPIRICAL METHOD

In order to determine surface settlements the equations (1) and (3) are applied. For stratified grounds, corresponding to Moscow geotechnical profiles I-VII, the abcisses of inflexion points of vertical displacement profilse i were determined with the help of equation

$$i = \sum_{i=1}^{n-1} K_i \cdot h_i + K_n \cdot h_n, \tag{5}$$

with n as number of soil strata in the profile; h_i as thickness of i-th soil stratum.

In order to elaborate an empirical method of surface settlements forecast for shallow service tunnels there were compared settlement profiles, calculated with equations (1) and (3), FEM PLAXIS 7.2 (2D analysis with Coulomb-Moore model option), and settlements, measured during construction of shallow service tunnels "Novobratsevo-Voikovskaya" (Figure 4) and on Gruzinsky Val Str. (Figures 5, 6).

Service tunnels "Novobratsevo-Voikovskaya" collector were mined with shield. Shield «BESSAC» (D = 3,5 m, H = 6,0 m, V_L = 1,4%.), was used between chambers No. 5-7, between chambers No. 10-13 shield «AVND 2500 AH» (D = 3,0 m, H = 7,0 м, V_L = 2,5 %.) was used.

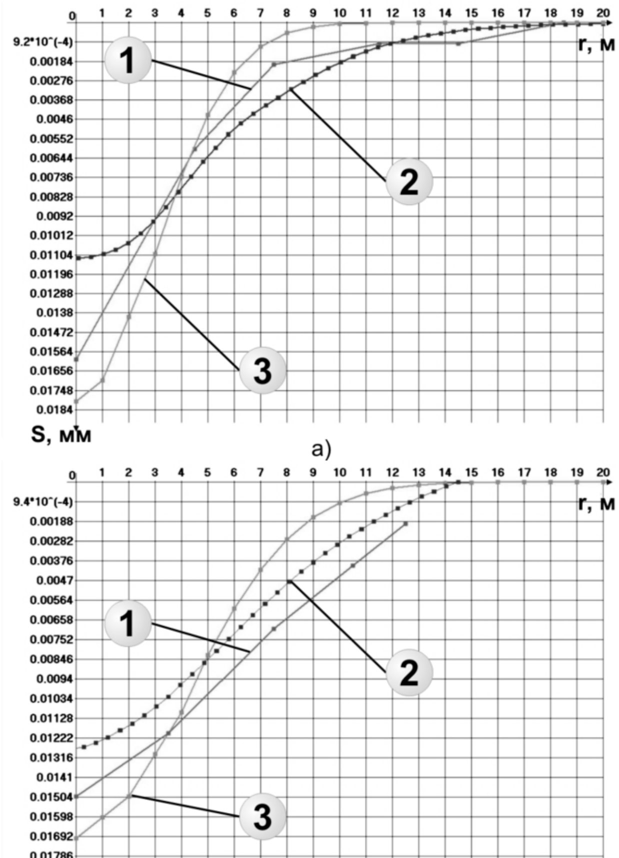

Figure 4. Profiles of surface settlements, induced by "Novobratsevo-Voykovskaya" service tunnel between chambers a) No. 5-7, b) No. 10-13: 1- measured settlements (by dedicated contractor Creat); 2- settlements, computed with PLAXIS; 3 – settlements as per Peck formula (1969), Burland et al. (2001).

Service tunnel on Gruzinsky Val Str**.** is being mined with "Lovat" shield (D = 4 m, H = 4,0 m, as per the shield passport V_L = 1,78 %.) in water saturated fine sands (Figure 5). Fill thickness is 4-6 m.

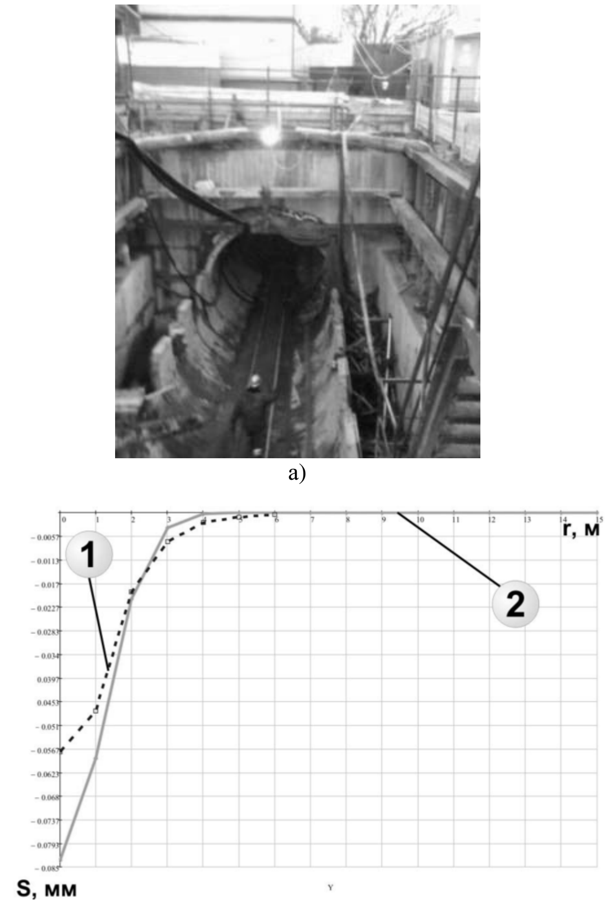

Figure 5. a) shallow service tunnel on Gruzinsky Val Str. for underground complex "Tverskaya zastava"; b - surface settlements profile: 1 - as per NIIOSP monitoring data, 2 – as per formula of Peck (1969), Burland et al. (2001).

Maximum settlement as per equation (1) for service tunnel on Gruzinsky Val Str. (for geotechnical profile для VII) is ~80 mm, while the measured value is 50…71 mm.

Comparison of the above settlement profiles has yielded that equation (1), proposed by (1969), Burland et al. (2001) overestimates the value of maximum settlement above the tunnel and underestimates the tunnel influence zone width B.

The width of the shallow service tunnel B i.e., horizontal distance from tunnel axis to the point, at which the surface settlement value stays within the geodetic measurement accuracy or is close to 0 in calculations.

Monitoring data of surface settlements above service tunnels and analytical data, obtained by empirical method of Peck (1969), Burland et al. (2001), prompt application of the following factors for Moscow geotechnical environment:

- reducing factor K_1 = 0,85 for the value of maximum settlement above tunnel, determined as per equation (3);
- increasing factor K_2 =1,3 for the width of settlement profile above tunnel, determined as per Peck (1969) empirical method for geotechnical profiles with predominant clay soils occurrence and K_2 =1,5 for profiles with predominant sand soils. For tentative analysis mean value K_2 =1,4 is recommended.

Approximate value of maximum surface settlement above shallow service tunnel $S_{v\,\max}$ may be determined, using the following equation with the account of correction coefficients:

$$S_{v\max} = K_1 (0.313 \cdot V_L \cdot D^2 / i), \tag{6}$$

with K_1 = 0,85 for I-VII types of geotechnical conditions; V_L as volume of ground loss in shallow service tunnel mining, D as diameter of shallow service tunnel.

In accordance with the available data on shallow service tunnels construction in Moscow the values of soil overcutting factor were assumed from 2% to 5%.

Relative differential settlements, caused by shallow service tunnels construction $\Delta S / l \sim S'(y)$ are determined, using equation (7) with surface curvature ρ~ $S''(y)$ as per equation (8).

$$S'(y) = S_{\max} \cdot e^{-y^2/2i^2} \cdot \left(-y/i^2\right), \tag{7}$$

$$S''(y) = \left(-1/i^2,\right) \cdot S_{\max} \cdot e^{-y^2/2i^2} \cdot \left(1 - y^2/i^2\right), \tag{8}$$

There have been plotted profiles of settlements, relative differential settlements, surface curvature, horizontal displacements above shallow service tunnels for typical geotechnical profiles I-VII in Moscow for shields, having D = 3.0 and 4.0 m; H = 4, 5, 6, 7 m; V_L =1, 2, 3 %.

There have been established approximate values of surface maximum settlements above shallow service tunnels, mined in geotechnical conditions of I-VII types in Moscow.

Tenatative values of influence zone width *B*, for shallow service tunnels (H = 4-8 m и D = 3-4 m) in Moscow shall be borrowed from Table 2, where $z_0 = H + D/2$. In this zone geotechnical monitoring shall be conducted.

Table 2. Rough values of influence zone width due to service tunnels construction

Geotechnical profile type	B
I	2,0 Z_0
II	1,5 Z_0
III	1,5 Z_0
IV	2,5 Z_0
V	1,5 Z_0
VI	2,5 Z_0
VII	1,2 Z_0

4 ASSIGNING PROTECTIVE MEASURES FOR EXISTING BUILD-UP AREA AND SERVICE LINES

Protective measures for buildings and service lines within the shallow tunneling zone impact are assigned for the case of deformations, exceeding limit values, specified in MGSN 2.07-01, Ilyichev et al (2003).

Surface deformations shall be determined from diagrams, based on equation (1), with the account of correction factors, while settlements of buildings by the method of Franzius & Addenbrooke (2002).

4.1 *Procedure for determining the width of zone for protection of buildings and service lines*

The protective zone width shall be established as per the following sequence.

1. Determine the value of limit extra deformations (maximum settlement, relative differential settlements, footing base curvature) for a building, depending on its structural condition category.

2. Determine dimensions of zones with excessive extra limit deformations of buildings..

3. The required zone of protective measures shall be assigned as the maximum of three zones, derived from three profiles (settlements, relative differential settlements and surface curvature).

5 CONCLUSIONS

Tentative forecast of ground deformations due to shallow service tunnels construction in Moscow is shown for seven most typical geotechnical profiles.

In order to predict surface settlements, induced by shallow service tunnels construction in Moscow, geotechnical environment correction factors are proposed to the known empirical method for predicting surface settlements, caused by construction of large diameter tunnels (for subway) at various depths, based on field monitoring and numerical simulation.

Tentative values of maximum surface settlements, caused by service tunnels construction with the help of different 3-4 m dia and 4-8 m deep shields in Moscow geotechnical environment, are given.

Recommendations are proposed for determining the zone of shallow service tunnels construction influence on the ground (the required zone of geotechnical monitoring).

A procedure has been developed for determining the width of the zone, in which protection of existing buildings and service lines is required.

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