PREDICTION OF GROUND DEFORMATIONS DUE TO CONSTRUCTION BY NATM TECHNOLOGIES OF URBAN TUNNELS

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Summary: *In the paper, basic principles of modified methods of urban tunnels construction under complicated geotechnical conditions are considered. Main components of ground deformation under construction of shallow tunnels by applying NATM technologies are analyzed, and empirical prediction is considered as a preliminary assessment.*

Key words: *NATM, urban tunnels, support, ground deformation, ground surface deformation.*

The economic growth of many cities and megalopolises has resulted in the need for improvement in transport infrastructures. As urban areas become more limited, underground structures such as tunnels are becoming more efficient in providing the required transport system. Transport tunnels in urban areas are predominately constructed at a shallow depth; however, the construction can cause serious problems of the ground deformation, especially in built-in areas. In these areas alongside with new structures, there are old masonries, which have architectural and historic value. Multistory buildings with masonry bearing walls without reinforcement, as well as their foundations possess relative low strength and stability. As a result, they are very sensitive to no uniform deformations. Under the construction and operation of tunnels, these structures require special protections.

In recent decades in tunnel construction under complicated urban architectural and geotechnical conditions, the application of the New Austrian Tunneling Method (NATM) (fig. 1) has extended [1]. This method and its modifications widely have been used in large cities of Europe, Asia and America. Alongside with the traditional technologies of NATM, there are different modifications such as Sprayed Concrete Lining (SCL) in England and Sequential Excavation Method (SEM) in America. These methods base on the following principles [1]:

- The level of deformation in the ground should be kept small so that the ground does not lose more of its initial stability than unavoidable and;
- The level of deformation of the ground should be large enough in order to activate the support of the ground as a closed arch and to optimize the usage of the support measures and the excavation;
- In the case of relatively large ground deformation, the temporary supports have to work across the excavated surface.

Conducting researches on the mode of deformation of the temporary supports by interacting with ground show that: in consideration of the relation “deformation – effective ground pressure (r/R –p)” (fig. 3) [3] noted that ground pressure “p” of the tunnel-excavated profile decreases according to the increase of the displacement of the profile to a minimum point “pmin” – point “B”. For construction methods based on NATM technologies, the displacement of the profile increases with the round length Rd and the diameter of the excavation. The freshly excavated length will be supported after a certain time by the installation of a lining, as indicated by point “A”. Due to further cutting and creep the lining will deform along lining response curve 3 until a quasi final state of stress is reached, as indicated by point “C”. After point “B” “detrimental loosening” starts and the required support pressure to stop the loosening increases greatly.

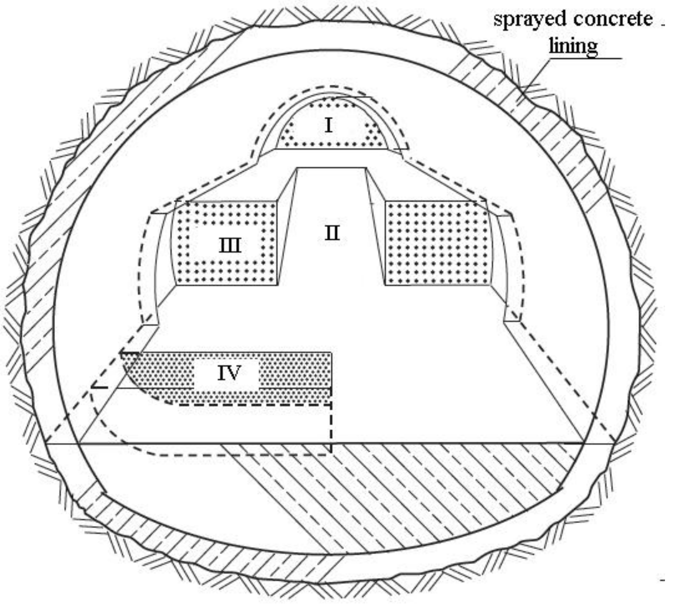

Figure 1. *Sequence of the excavation in tunnel construction by applying NATM technologies: I – crown excavation; II – center bench excavation; III – lateral bench excavation; IV – invert excavation*

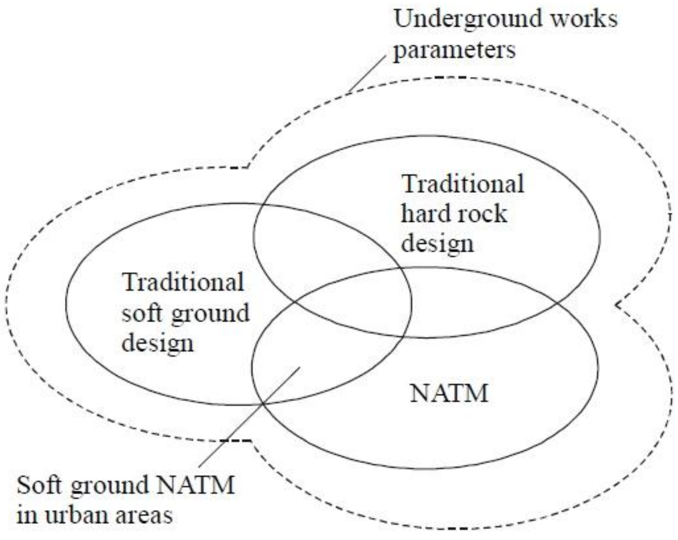

Figure 2. *Interrelationships of tunnel design philosophies*

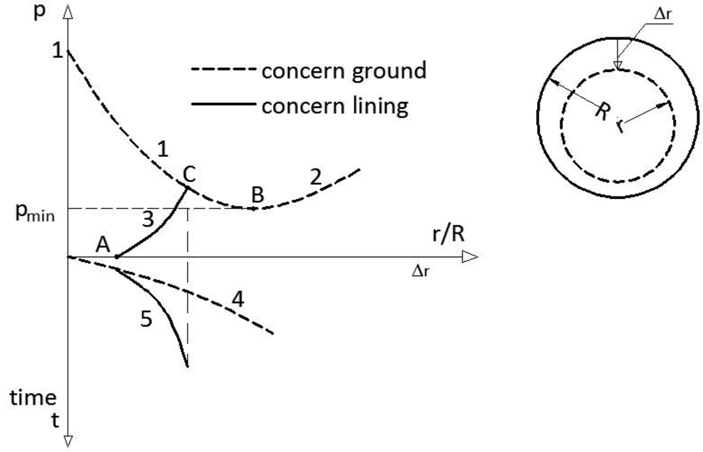

Figure 3. *The interaction between the ground and the support (sprayed concrete lining): 1 – ground response curve; 2 – loosening curve; 3 – the support response curve; 4, 5 – dependence of the displacement of tunnel-excavated profile on time respectively in the case of absence and presence of the support. po – initial effective ground pressure on the tunnel-excavated profile (radius R) and p – effective ground pressure on the tunnel-excavated profile with the radius r*

For tunnel construction by application of the technologies of NATM, the main causes of the ground deformation around the tunnel-excavated profile are illustrated in fig. 4. Ground movement (A) towards an unsupported tunnel heading can be reduced by shortening the round length R_d and applying supports. The radial ground movement (B) towards the lining is relatively large as an initially ductile sprayed concrete lining is used for temporary support. Stiffness and strength of sprayed concrete change by time, and reach the strength of $R_c \approx 180$ MPa after only 24 hours [1].

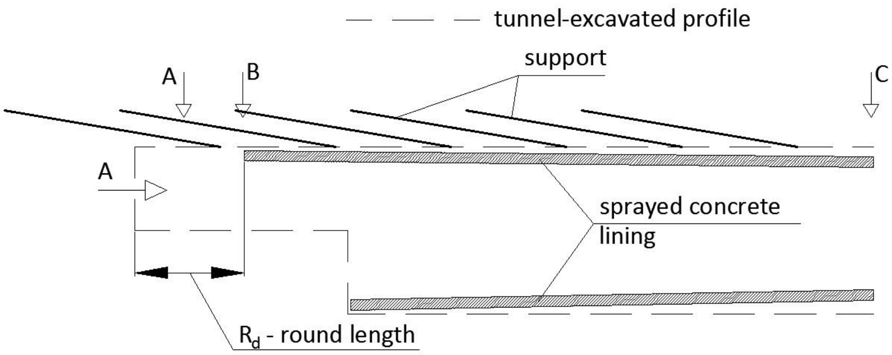

Figure 4. *Main components of ground deformations around the tunnel-excavated profile: A – ground movement towards unsupported heading, B – radial ground movement towards the lining and C – radial ground movement towards the lining due to consolidation.*

Although enormous advances in computer based numerical methods for calculating ground deformations are being made, these are still some advantages of using simple empirical based methods in soft ground due to its rapidity, conservation of risk assessment and reality for long masonry walls. Independently on construction methods, green field surface displacements can be described based on Gaussian function (fig. 5). The vertical displacements at the transverse plane y is:

$$S_v(y) = S_{v\max} * e^{-y^2/2i_y^2},\qquad (1)$$

Where: S_{vmax} – the maximum displacement directly above the tunnel centerline; y – transverse horizontal distance from the tunnel centerline; i_y – transverse horizontal distance from the tunnel centerline to the point of inflection of the trough.

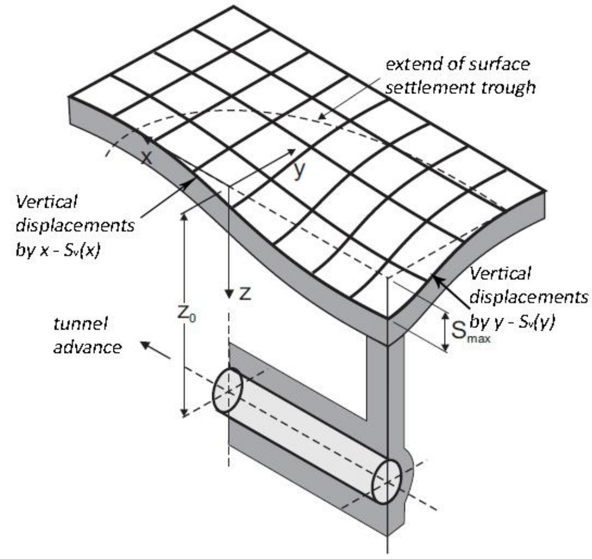

Figure 5. *Character of the ground surface settlements under tunnel construction: y – the transverse direction; x – the longitudinal direction (along the tunnel centerline)*

In consideration of the ground volume loss, the above vertical displacements can be defined as:

$$S_v(y) \approx \frac{A_t}{i_y * 2\sqrt{\pi}} * GRL * e^{-y^2/2i_y^2},\qquad (2)$$

Where: A_t – the excavated tunnel area,

GRL = V_t / A_t – ground loss ratio, V_t – ground loss (fig. 6)

The parameter GRL depends on construction technologies, geotechnical conditions, and tunnel profiles. For NATM "GRL" is defined as a function of round length Rd (fig. 4) and tunnel size. The experimental results show that the parameter GRL is from 1% to 2%.

The distribution of ground surface horizontal displacements is given by:

$$S_h(y) = \frac{y}{z_0} * S_{v,\max},\qquad (3)$$

Where: z_0 – the vertical distance from the ground surface to the tunnel axis (fig. 5).

The diagrams of horizontal displacements S_h(y) and vertical displacements S(y) of the ground surface are shown in fig. 6. The ground surface deformation depends on "i_y", its value, in the case of shallow tunnels, is determined by parameter "z_0" and the size of the tunnel profile [4]:

$$\frac{2i}{D} = \left(\frac{z_0}{D}\right)^{0,8},\qquad (4)$$

Where D - the diameter of the tunnel.

The settlement $S_v(x)$ above the tunnel center line at location x can be obtained from equation (5). Generally, the settlement directly above the tunnel face coincides with $0,5S_{vmax}$, but with the presence of supports, the settlement decreases:

$$S_v(x) = S_{v\max} * \frac{1}{i_y * 2\sqrt{\pi}} * \int_{-\infty}^{x} e^{-x^2/2i_y^2}, \quad (5)$$

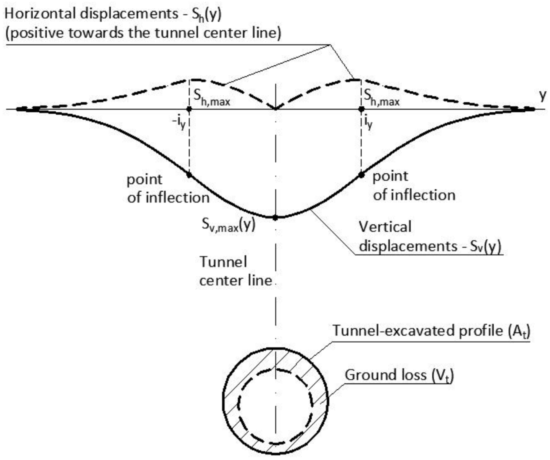

Figure 6. *The horizontal and vertical displacements of the ground surface at the transverse direction of the tunnel center line*

Based on the above analysis of the prediction of the ground surface under construction of tunnels by the technologies of NATM, we conclude that:

- Application of the technologies of NATM in complicated urban architectural and geotechnical conditions is continuously extended;
- Minimization of nonuniform deformation of the ground surface, where reinforcement concrete and masonry buildings are of architectural and historical value are located, is one of the key issues in shallow urban tunnels construction;
- A detailed assessment of the ground surface deformation under construction of tunnels by application of NATM technologies requires analysis of the influence of the sequential excavations on the ground deformation;
- In the prediction of the ground surface deformation, empirical approach based on Gaussian function can be used;
- To solve the above issues it is necessary to conduct theoretical and experimental studies for determination of the manifestation of the ground and its surface deformation under shallow tunnels construction in complicated urban architectural and geotechnical conditions by application of the technologies of NATM .

References

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