NUMERICAL ANALYSIS OF SUBSIDENCE INDUCED BY CONSTRUCTION OF A NATM TUNNEL

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Summary: *The design of urban tunnels, often constructed at shallow depths, in soft ground, requires an appropriate prediction of ground surface settlements. Control of surface settlements is of particular importance in open-face tunneling. This paper presents a finite element analysis of subsidence above conventionally constructed Steinhaldenfeld tunnel in Stuttgart, Germany. The surface settlement profiles obtained by calculations were compared with the empirical Gaussian curve and the profile obtained by measurements.*

Keywords: *Tunnel, settlement, finite element method*

1. INTRODUCTION

The construction of a tunnel at a shallow depth, in soft ground, leads to subsidence of the ground surface which in urban areas can cause damage to existing structures and facilities. This problem is of particular importance in open-face tunneling, i.e. when tunnels are constructed using New Austrian Tunneling Method (NATM) or open face shield. It is therefore necessary to assess potential subsidence before the start of tunnel construction. However, this task is not simple. Methods for the evaluation of ground surface settlements due to tunneling can be classified into three categories: empirical methods, analytical solutions and numerical methods. Empirical and analytical methods are relatively simple and useful procedures, however, the potentials of their application are limited. In order to obtain an adequate assessment of ground settlements, the computation methods should take into account a number of factors such as: 3D effects of tunnel construction, method and details of construction, depth and diameter of the tunnel, initial stress state and stress-strain behavior of the soil around the tunnel. This can be achieved by applying advanced numerical methods. The finite element method (FEM) is a flexible tool that has been adopted by many authors.

This paper presents a finite element analysis of subsidence above conventionally constructed Steinhaldenfeld tunnel in Stuttgart, Germany. The surface settlement profiles obtained by computations were compared with the empirical Gaussian curves and the settlement profile obtained by measurements.

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2. METHODS FOR ESTIMATING SUBSIDENCE DUE TO TUNNEL CONSTRUCTION

Methods for estimating subsidence due to tunnel construction can be divided into three categories: empirical methods, analytical solutions and numerical methods.

Empirical methods

Based on ground settlement measurements in a number of tunnels, it has been established [1] that the transverse settlement profile can, quite well, be represented by a Gaussian normal distribution function. This is widely accepted in practice and represents a well-known and widely used empirical method for estimating the subsidence of the ground surface. Vertical ground surface settlements in the transverse direction are given by the following expression:

$$S_v(x) = S_{v\max} \exp\left(-\frac{x^2}{2i^2}\right) \tag{1}$$

where S_{vmax} is the maximum settlement which occurs above the tunnel axis, x is the horizontal distance from the tunnel axis, and i is an important parameter that defines the width of the transverse settlement profile and represents the horizontal distance from the tunnel axis to the profile inflexion point, as shown in Figure 1.

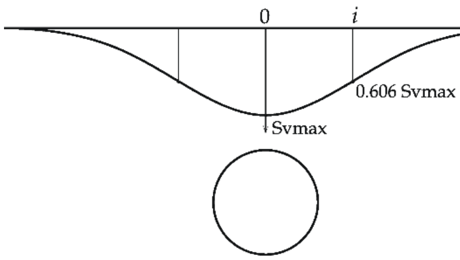

Figure 1. Transverse settlement trough - Gaussian curve

Ground subsidence due to tunnel construction is usually characterized by a parameter volume loss V_L. It is the ratio of the volume of soil that deforms into a tunnel opening V_S and the theoretical volume of a tunnel opening $V_L = V_S/(\pi D^2/4)$. For tunnels in clay (under constant volume condition) it can be assumed that volume V_S is equal to the volume (per unit length of tunnel) of the settlement trough $V_S = 2.5 \cdot i \cdot S_{vmax}$ (obtained by integration of the expression 1). Thus, the maximum settlement of the ground surface, for a given diameter of tunnel D, can be expressed in the form:

$$S_{v\max} = 0.313 \cdot V_L \cdot \frac{D^2}{i} \tag{2}$$

The parameter V_L depends on the tunnel construction method and the type of soil. In order to estimate the parameter V_L, the experience related to a certain tunneling technique and geotechnical conditions is of particular importance. Based on the data of subsidence monitoring, it was found that open face tunneling (NATM or open face shield) gives higher values of volume loss than closed face tunneling (EPB shield or slurry shield). According to Mair and Taylor [2], Mair [3] typical V_L values in open face tunneling in soft ground are generally in the range of 1-3%, while lower values are obtained in closed face tunnel construction. With careful operation of the EPB shield, very small V_L values of as much as 0.25 to 0.5% can be achieved [4]. Burland et al. [5] have emphasized the importance of the parameter volume loss for subsidence due to tunnel construction and proposed that the limit values of this parameter be specified within the contract documents for tunnel construction.
The width of the transverse settlement profile is defined by the parameter *i* which represents the horizontal distance of the profile inflexion point from the tunnel axis (Figure 1). Based on the measurements of the ground surface settlements above tunnels in clays, O'Reilly and New [6] proposed a linear relationship:

$$i = K \cdot z_0 \tag{3}$$

with K = 0.5 for clay, where is z_0 the depth of the tunnel axis below the ground surface. Mair and Taylor [2], based on a large number of data from tunnels built in clay and sand, obtained K values in the range of 0.4 to 0.6 with a mean value of K = 0.5 for clay, and values of 0.25 to 0.45 with a mean value of 0.35 for sand.
Empirical methods are often used in engineering practice. They provide reasonable prediction of ground surface settlements if site conditions are well known, and if design parameters are appropriately calibrated.

Analytical methods

Analytical methods provide simple solutions in closed form, but their application in practice is limited as they are often based on idealized assumptions regarding tunnel geometry (circular cross-section), soil homogeneity, constitutive soil models and definitions of boundary and initial conditions. Several analytical solutions for predicting soil movements due to tunnel construction have been proposed in the literature [7-10].

Numerical methods

Empirical and analytical methods are simple and useful procedures for settlement estimation, but the potentials of their application are limited. Since it is practically impossible to get a closed form solutions for extremely complex problems of tunnel-soil interaction, it is necessary to use advanced numerical methods. The finite element method is a flexible tool that has been adopted by many authors. The application of the finite element method allows to take into account: complex geometry of the problem, construction methods, soil heterogeneity, non-linear behavior of soil and soil-structure interaction.
For adequate analysis of stress-strain states in the tunnel lining and soil, it is essential to consider the partial stress relief, i.e. deformations of the excavation surface at the tunnel working face that occurred before the installation of the lining. This can, above all, be achieved by three-dimensional FE modeling which simulates the progress of tunneling

works and stress-strain changes that take place at the temporary working face. The 3D process of tunnel construction is usually simulated using a step-by-step procedure. In this method, the first step is to establish the initial (in-situ) stress state in the ground, which is followed by simulation, step-by-step, of excavation and lining installation sequences. The tunnel excavation was modeled by successive removal of elements in front of the tunnel face to simulate an unsupported excavation with a given round length, while successively installing lining elements to support the previous excavation. The simulation of tunneling works has to be made on the length that is sufficient to obtain a steady state behind the tunnel face. This procedure has been applied for simulating open face tunnel construction by conventional methods (NATM) or open face shield [11-21]. When closed-face shield tunneling is simulated, the modeling can include some construction details such as the support pressure at the tunnel face, grouting pressure, etc.

However, because of the computational effort involved in 3D FE modeling, two-dimensional FE models are still commonly used in routine geotechnical design. When the process of tunnel construction is modeled in plane strain, at least one assumption must be made in order to account for partial stress relief and ground movements occurring at the tunnel face prior to lining installation. Various methods that take into account 3D effects of tunneling within simplified 2D plane strain analysis have so far been proposed in literature [22-25]. An overview of the methods can be found in [26]. The most commonly used method for 2D modeling of open-face tunnel construction is the stress (load) reduction method (λ - method), which is actually a FE utilization of the convergence-confinement method [22]. The partial stress relaxation that occurs at the tunnel working face is introduced into the 2D model via the parameter λ which represents the percentage of unloading of the initial stresses before lining installation. Thus, at a prescribed value λ the lining is installed, so that the lining receives a load equal to $\sigma^*=(1-\lambda)\sigma_0$, where σ_0 is the initial soil stress. The stress reduction factor λ depends on a number of factors such as soil properties, tunnel geometry, construction method and the round length. The results presented in [21] suggest that the stress reduction factor significantly depends on the shear strength parameters of soil, where its value increases with a decrease in the cohesion or angle of shearing resistance. This is because the weaker soil leads to higher deformations at tunnel face prior to the installation of lining. It has been shown [21] that 3D and 2D analyses give similar surface settlement troughs when an appropriate value of the stress reduction factor is adopted. The stress reduction factor λ can be calibrated based on the comparison of 2D and 3D results. In practice, parameter λ is often estimated based on previous engineering experience with similar tunneling conditions or monitoring data.

3. FINITE ELEMENT ANALYSES OF STEINHALDENFELD TUNNEL

In this study, finite element analyses of conventionally driven Steinhaldenfeld tunnel were performed using the stress (load) reduction method. Steinhaldenfeld tunnel is part of the subway system of the city of Stuttgart, Germany. The tunnel was built using the New Austrian Tunneling Method (NATM). The top heading was excavated first, over the entire tunnel length, and later the invert was excavated. In the paper, the top heading excavation was simulated. Figure 2 shows the two-dimensional FE mesh adopted for analyses. The finite element analyses presented in this paper were carried out using DIANA Finite

Element Analysis code (TNO DIANA BV, Delft). DIANA is a multi-purpose finite element program that enables modeling of phased construction [27]. The soil was modeled by eight-node quadrilateral isoparametric plane strain elements, whereas tunnel lining was modeled by three-node curved infinite shell elements. Boundary conditions were set to prevent displacement in horizontal direction at the vertical boundaries and to prevent displacement in all directions at the bottom boundary of the mesh. An additional condition was set to prevent rotation around the axis perpendicular to the mesh in the lining node in symmetry plane.

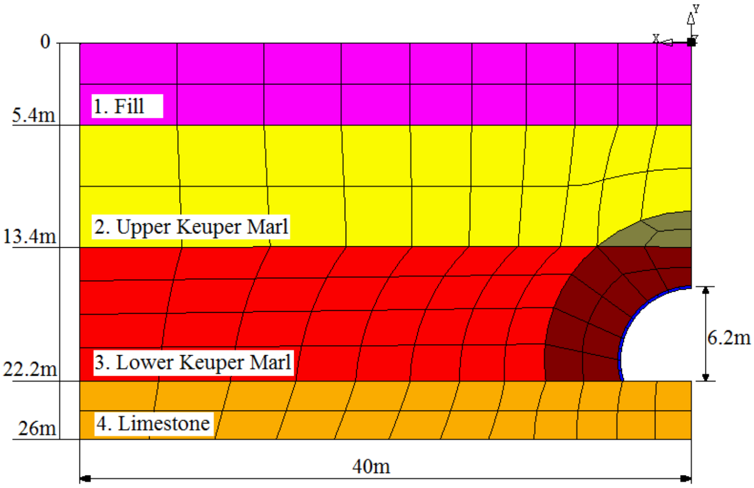

Figure 2. Two-dimensional FE mesh for Steinhaldenfeld tunnel

The ground profile consists of the top layer of manmade fill underlain by two layers of weathered Keuper Marl which rest on limestone. Ground parameters obtained from site investigation [28] are listed in Table 1. Since the limestone is significantly stiffer than the marl, the finite element mesh was not extended much into the limestone. Groundwater was not considered in the FE analyses because the actual groundwater table was located below the bottom mesh boundary [29]. Drained ground behavior was modeled using the elasto-plastic Mohr-Coulomb (MC) model and the Duncan-Chang (DC) model [27]. MC ground parameters are listed in Table 1 whereas the additional ground parameters for the DC model are listed in Table 2. The ground directly around the tunnel opening was reinforced with nails and this was taken into account in the model by increasing the cohesion by 25 kPa (according to [28]). The sprayed concrete lining, 0.25 m thick, was modeled assuming linearly elastic behavior of concrete with γ = 24 kN/m^3, E = 15 GN/m^2 and ν = 0.2.
Initial soil conditions were established at the start of each FE analysis. Initial stresses were specified using the values of the unit weight and the coefficient of lateral earth pressure at rest K_0 listed in Table 1. 2D analyses were conducted using the stress reduction method (λ method). Starting from the initial geostatic stress state, the soil elements within the tunnel boundary were removed and the lining was installed at a prescribed value λ, at which point the stress reduction at the boundary was $\lambda \cdot \sigma_0$, where σ_0 is the initial soil stress. In this study, value of the stress reduction factor λ was calibrated to obtain the same ground

surface settlement above the tunnel axis by 2D FE analysis as the value obtained by measurements.

Table 1. Steinhaldenfeld ground parameters of the MC model from site report [28]

Layer	γ (kN/m^3)	E (MPa)	ν	c' (kPa)	ϕ' (°)	K_0
1. Fill	20	15	0.37	10	25	0.57
2. Upper Keuper Marl	24	100	0.2	25	25	0.9
3. Lower Keuper Marl	23	60	0.35	25	25	0.9
4. Limestone	23	750	0.2	200	35	0.6

Table 2. Additional ground parameters for the Duncan-Chang model

Layer	Ei (MPa)	Eur (MPa)	ν_{ur}	n	E_{tmin} (MPa)	σ_{3min} (kPa)
1. Fill	15	30	0.2	0.5	10	30
2. Upper Keuper Marl	100	100	0.2	0.4	33	184
3. Lower Keuper Marl	48	60	0.2	0.4	16	361
4. Limestone	575	750	0.2	0.3	190	328

4. RESULTS OF ANALYSIS AND DISCUSSION

Figure 3 presents the ground surface settlement troughs obtained from the conducted 2D FE analyses and the empirical Gaussian curves with i = 0.5z_0 and i = 0.45z_0. Also, the measured settlements [29] are shown in the Figure 3. As already mentioned, the stress reduction factor λ was calibrated based on measurement data. The best agreement with the measured value s_{max} was obtained at a stress reduction of about 70%, i.e. for the MC model at λ = 0.73, and for the DC model at λ = 0.70. Möller and Vermeer [29], for this particular conventionally driven tunnel, also found the best fit for the settlement analysis at a stress reduction of about 70%, i.e. for the HS (Hardening soil) model at β = 1-λ = 0.36 (λ = 0.64) and for the HS-Small (Hardening soil with small strain stiffness) model at β = 0.28 (λ = 0.72). The obtained values of stress reduction correspond well with the findings of other studies [30, 21].

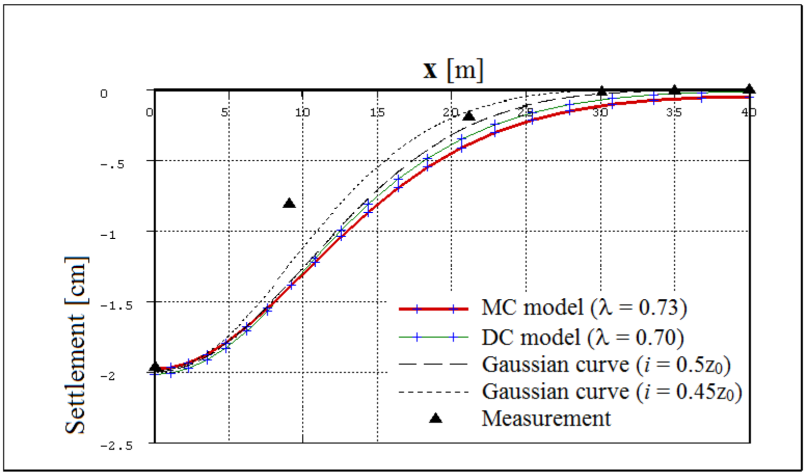

Figure 3. Transverse ground surface settlement profiles for Steinhaldenfeld tunnel

As can be seen in Figure 3, the shape of the computed settlement profiles corresponds well to the Gaussian curve with $i = K{\cdot}z_0 = 0.5z_0$, which is the mean value of K for tunnels in clay, as stated in Section 2. Möller and Vermeer [29] obtained the settlement trough of similar shape using HS model and narrower transverse settlement trough, which corresponds to the Gaussian curve with $i = 0.42z_0$, using the HS-small model (which take into account the small strain stiffness of soil, i.e. the high soil stiffness at very small strains). Möller and Vermeer [29] noted that the available empirical data were limited (as there were only two measurement points within the settlement trough), and that the empirical Gaussian curve also would question the accuracy of one of the measurements.

5. CONCLUSIONS

Design of urban tunnels, which are often constructed at shallow depths in soft ground, requires an adequate assessment of the subsidence of the ground surface. This problem is of particular importance in open-face tunneling (NATM or open face shield). Empirical methods, which are often used in engineering practice, provide reasonable prediction of ground surface settlements if site conditions are well known, and if design parameters are appropriately calibrated. Analytical methods provide simple solutions in closed form, but their practical application is limited, since they are often based on idealized assumptions. Advanced numerical methods are required for modeling complex tunnel-soil interaction problems. Tunnel construction is a three-dimensional process. A full 3D FE analysis is required to simulate progress of tunneling work and stress-strain changes that take place at the temporary working face. However, because of computational effort involved in 3D modeling, 2D models are still commonly used in routine geotechnical design. The most commonly used method for 2D modeling of open-face tunnel construction is the stress (load) reduction method (λ - method).

In this study, FE analyses of conventionally driven Steinhaldenfeld tunnel were performed using the stress (load) reduction method. The ground surface settlement troughs obtained from FE analyses were compared with empirical Gaussian curves and measured settlements. The stress reduction factor λ was calibrated based on measurement data, and stress reduction of about 70% was obtained (for the MC model $\lambda = 0.73$, and for the DC model $\lambda = 0.70$). A similar value of stress reduction for this tunnel was obtained by Möller and Vermeer [29] (for HS and HS-Small models). The above relatively high λ values correspond to the findings of other studies [30, 21]. The shape of the computed transverse settlement profiles corresponds well to the empirical Gaussian curve with $i = K \cdot z_0 = 0.5z_0$, which is the mean value of K for tunnels in clay [6, 2]. Möller and Vermeer [29] obtained narrower transverse settlement trough by taking into account the small strain stiffness of soil, i.e. the high soil stiffness at very small strains (HS-Small). The shape of the settlement trough depends on the magnitude of horizontal initial stresses wherein the settlement trough becomes wider and shallower with increasing horizontal initial stress. It has been noted by several authors that the finite element analysis of tunneling predicts too wide and shallow transverse settlement trough, when compared with field data, especially in stiff clay under high K_0 condition ($K_0>1$) and that improved prediction can be achieved by modeling small-strain nonlinearity and soil anisotropy.

Full 3D FE modeling enables prediction of ground surface settlements without the need for an initial assumption regarding volume loss or proportion of unloading before installation of lining. When the tunnel construction process is modeled using the stress reduction method, the controlling parameter λ must be assumed. It has been shown [21] that the settlement trough predicted by 2D analysis agrees well with the 3D results when an appropriate value of the stress reduction factor is adopted. However, the λ-factor is difficult to assess, as its value depends on a number of factors such as soil properties, tunnel geometry and the round length. It can be calibrated based on the results of 3D analysis, previous engineering experience with similar tunneling conditions or monitoring data.

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НУМЕРИЧКА АНАЛИЗА СЛЕГАЊА УСЛЕД ИЗГРАДЊЕ ЈЕДНОГ НАТМ ТУНЕЛА

Резиме: *Пројектовање тунела који се налазе у урбаном подручју, и често на малој дубини, у меком тлу, захтева адекватно предвиђање слегања површине терена. Контрола слегања је од нарочитог значаја код изградње тунела са отвореним челом. У раду је приказана анализа применом методе коначних елемената слегања изнад конвенционално грађеног тунела Steinhaldenfeld у Штутгарту, Немачка. Извршено је поређење профила слегања површшине терена добијених прорачунима са емпиријском Гаусовом кривом и профилом који је добијен мерењима.*

Кључне речи: *Тунел, слегање, метод коначних елемената*