

# The influence of different tunnel cross sections on surface settlement

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## Abstract

*The analyze of tunnel induced surface settlements is of high importance in tunneling construction especially in urban areas. Excessive settlements can trigger potential damage to surrounding structures. The aim of this paper is to study the influence of different tunnel cross section on ground surface settlement, an aspect which hasn't been studied before. Empirical equations which assume the settlement profile close to an inverse Gaussian distribution curve and 3D FEM will be developed in order to asses transverse settlement profiles induced by tunneling construction.*

## Rezumat

*Analiza tasării suprafeței terenului datorită construirii tunelului este un subiect de mare importanță, în special în zonele urbane. Tasăriile excesive pot declanșa avarii semnificative construcțiilor învecinate. Scopul acestei lucrări este să studieze influența diferitelor secțiuni de tunel asupra tasării terenului de la suprafață, un aspect care nu a mai fost studiat până la această dată. Ecuații empirice, care consideră profilul tasării ca o distribuție inversă a curbei lui Gauss, și analize 3D cu ajutorul elementului finit vor fi elaborate, având ca scop determinarea tasării transversale datorate constuirii tunelurilor.*

**Keywords:** surface settlements, ground loss, cross sections, FEM, empirical methods

## 1. Introduction

Settlements appear at the surface due to radial deformation around the excavation but also due to face deformation. Immediate surface settlements can occur due to a large number of sources. The multitude of sources can be lumped into two main categories: ground water depressurization and loss of ground. The first one is normally intentionally produced, in order to lower the water level during construction and can be produced by the tunnel itself which is used as a drain. The second main factor that causes the soil to settle is the "loss of ground". This phenomenon is strongly influenced by the excavation technique, tunnel diameter, tunnel depth and soil conditions [5].

In this paper only the short term behavior will be treated, meaning that only the first lining support will be provided. The main objectives of the first support are to stabilize the tunnel heading and to minimize the ground movement. On the other hand, the second lining function is to permit the tunnel to be operated over the design life [7].

The choice of the cross section is influenced by two main important factors: construction and

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structural approaches. In addition, the costs for excavation, lining and bending movements play an important role [1]. The purpose of this paper is to analyze the impact of different cross section on the surface settlements. The tunnels that will be analyzed are situated to the same depth, having the same area of excavated soil. Four different cross sections will be modeled: circular, horizontally oval, vertically oval, mouth (horseshoe) profile.

Numerical analyses and empirical methods will be used in conjunction in order to assess the surface deformation induced by the tunnel construction. A three dimensional approach will be implemented in the finite element analyses, which will allow the modeling of the construction phases and the advancement of the tunnel face.

The scope of this paper doesn't include the evaluation of surface structures damage caused by the tunneling induced settlements nor any soil stabilization or improvement methods.

## 2. Empirical formulations for surface settlements

Surface settlements in a transverse section are closed to an inverted Gaussian distribution, which is defined by two important parameters:  $S_{vmax}$  and  $i$  [5].

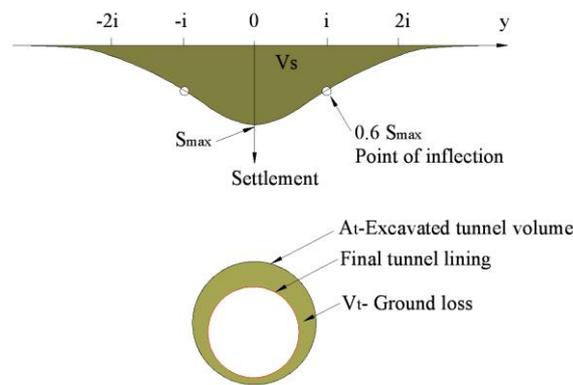


Figure 1. Transverse settlement – Gaussian curve. [3]

In many cases the settlement volume  $V_s$  is considered to be equal to the ground loss  $V_t$ , especially for fine grained soils in the short term. For coarse-grained soils the surface settlement through is generally smaller than the volume loss at the tunnel, and a reason for this can be the elastic rebound of deep layers and dilation and shearing of the soil directly above the tunnel [5].

$$S_v(y) = S_{vmax} \cdot e^{-\frac{y^2}{2i^2}} \quad [2] \quad (1)$$

$S_v(y)$  - is the surface settlement

$S_{vmax}$  - is the maximum settlement above tunnel axis

$i$  - is the horizontal distance from the tunnel axis to the point of inflection of the settlement trough

$y$  - is the horizontal distance from the tunnel axis

$$V_s = \sqrt{2\pi} \cdot i \cdot S_{vmax} \quad (2)$$

$V_s$  - represents the settlement volume (surface settlement through).

The ground loss represents the volume of the ground that has deformed into the tunnel after the tunnel was constructed [2]. The volume loss ratio (ground loss ratio GRL) is the ratio between the volume loss and the tunnel volume per unit length.

$$GRL = V_L = \frac{V_t}{A_t} \approx \frac{V_s}{A_t} \quad (3)$$

$A_t$  - represents the tunnel volume per unit length

$$S_{vmax} \approx \frac{A_t}{i \cdot \sqrt{2\pi}} \cdot GRL \quad (4)$$

$$S_v(y) = \frac{A_t}{i \cdot \sqrt{2\pi}} \cdot GLR \cdot e^{-\frac{y^2}{2i^2}} \quad [2] \quad (5)$$

The  $i$  value, which represents the horizontal distance from the tunnel axis to the point of inflection of the settlement trough, is based on field observations and model tests and can be expressed as:

$$i = k \cdot z_0 \quad (6)$$

-where  $z_0$  is the depth from top surface to the tunnel axis.

It depends mainly on tunnel cover to tunnel diameter ratio and soil conditions but not on the tunnel diameter. The constant  $K$  is the through parameter depending strongly on the soil nature [5].

$$i = \frac{i_1 + i_2 + i_3}{3} \quad [4] \quad (7)$$

$$i_1 = 0.386 \cdot Z_0 + 2.84 \quad (\text{Arioglu, 1992}) \quad (8)$$

$$i_2 = 0.5 \cdot Z_0 \quad (\text{Glossop, 1978}) \quad (9)$$

$$i_3 = 1.392 \cdot \left(\frac{D}{2}\right) \cdot \left(\frac{Z_0}{D}\right)^{0.704} \quad (\text{Arioglu, 1992}) \quad (10)$$

The volume loss ratio is strongly dependent on the equipment and the construction process. For shield machine it can reach values in the range of 0.5~1.0% and for sequential excavation method 0.8~2%, all this values are noted for homogeneous grounds. [3]

Only few attempts have been done to develop analytical methods till nowadays. Sagaseta presented in 1987 a close-form solution to obtain strain field in isotropic and homogeneous soil. In 1996, Verruijt and Booker presented an analytical solution for tunnels in homogeneous elastic half space using an approximate method suggested by Sagaseta for the case of ground loss. The analytical methods are not the scope of this paper.

### 3. Finite element method

Finite element methods allow the computation of ground displacement at every point within the ground. The geometry, initial conditions, excavation stages and ground behavior can be properly modeled using the numerical approach. For the finite element method Abaqus software was used. Since the problem of surface settlements due to tunneling construction represents a 3D problem, the analyzed tunnels were investigated using a 3D approach. This approach allows the modeling of the construction phases and the advancement of the tunnel face.

The main concern of the paper is to establish the influence that different cross section of tunnels have on the surface settlements. A circular tunnel with a radius of 5 meters, a horizontally oval, a vertically oval and a mouth profile (horseshoe) tunnels will be analyzed, all having the same area of excavated soil fig.(2).

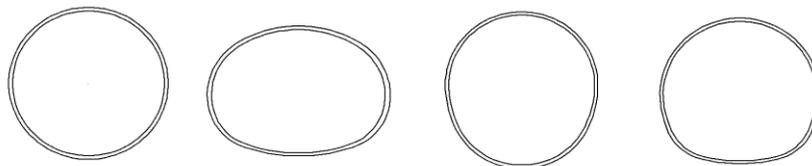


Figure 2. Analyzed cross section: circular, horizontally oval, vertically oval, mouth profile or horseshoe.

Two types of analyses will be developed to assess the surface settlements for different cross section: Firstly, the vertical stress and the horizontal stress are considered to be equal, and secondly the vertical stress is assumed to be two times higher than the horizontal one.

The model has a width of 50 m, and the same depth fig.(3). For the analysis a number of 20 excavation steps were modeled. The tunnel is encounter at a depth of 25 m, a depth measured from the ground surface to the tunnel axis. The model is fixed laterally and at the bottom, the top surface being free of deformation.

An elastic approach was analyzed, adopting the following characteristics for the soil: Young's modulus  $2e+09$  Pa, Poisson ratio 0.3 and a unit weight of  $24 \text{ kN/m}^3$ . For the shotcrete the considered characteristics are: Young's modulus of  $15e+09$  Pa, Poisson ratio of 0.2 and a unit weight of  $25 \text{ kN/m}^3$ . The thickness of the lining has a value of 0.3 m

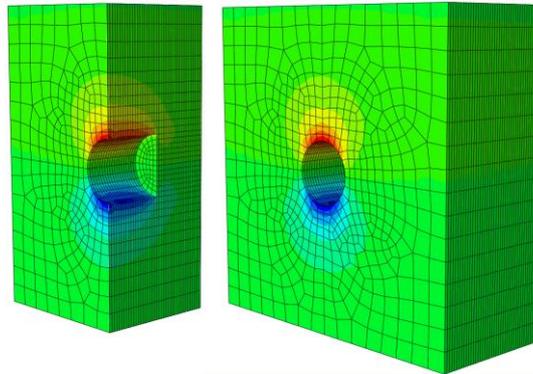


Figure 3. 3D model- Step 10-half model (left side), last step -whole model (right side).

A continuum approach was used to model both the soil and the shotcrete support using linear hexahedral elements of type C3D8R fig.(4). The C3D8R element stands for eight node brick continuum 3D elements with reduced integration (1 integration point). The integration point is situated at the middle of the element [8]. A number of approximately 26019 nodes and 23104 elements were used, the value of elements varying by  $\pm 10\%$  depending on the cross section that was used.

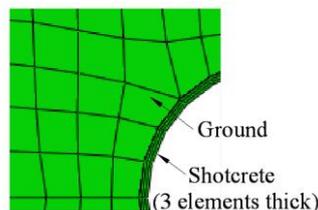


Figure 4. Mesh C3D8R-detail tunnel

The vertical stress which is assumed to vary linearly with depth was defined using the initial conditions. In order to do this an additional step is model which should be in equilibrium with the applied gravity loads and the boundary conditions. For this step the initial time increment and the total time specified should be the same. The reason for this is because the initial stresses are applied fully at time zero and the equilibrium can be reach, as a result there is no need of an increment since the step will converge in one increment [8]. Each step includes the excavation of 1 m and the lining installation.

The model is composed by 2 parts, one representing the soil and the other the tunnel lining. In the geostatic step the lining is removed and is added afterwards to each corresponding step follow-up the tunnel excavation. A tie contact formulation was used to tie the two surfaces –soil and lining. This interaction constrains each of the nodes on the slave (shotcrete lining) to have the same value of displacement as the points in the master surface (soil) that it contacts.



Figure 5. Master/slave surfaces. Node to surface (left side), node to node contact (right side) [9].

The contact formulation is to be used in Abaqus when two parts are interacting. The contact formulation is set between the tunnel perimeter of the ground and the outer edge of the shotcrete. The master –surface can penetrate into the slave-surface but not the other way around, meaning that the nodes of the slave-surface cannot penetrate into the master-surface [9].

#### 4. Results

Fig. (6) left, shows the transverse surface settlement profile for the analyses where  $k = 1$ . The maximum displacement is 4.8 mm for the horizontally oval shape tunnel. This situation was expected, since this cross section is normally used when the horizontal in situ stress is greater than the vertical one.

The smallest value at the surface settlement is 3.5 mm for the vertically ovoid case. This can be anticipated since a vertical ovoid tunnel will be proper when the vertical stress is much higher than the horizontal one. Therefore, in this analysis, since the stresses are equal, the vertical displacement is quite small. The difference between the upper range values is approximate 27%.

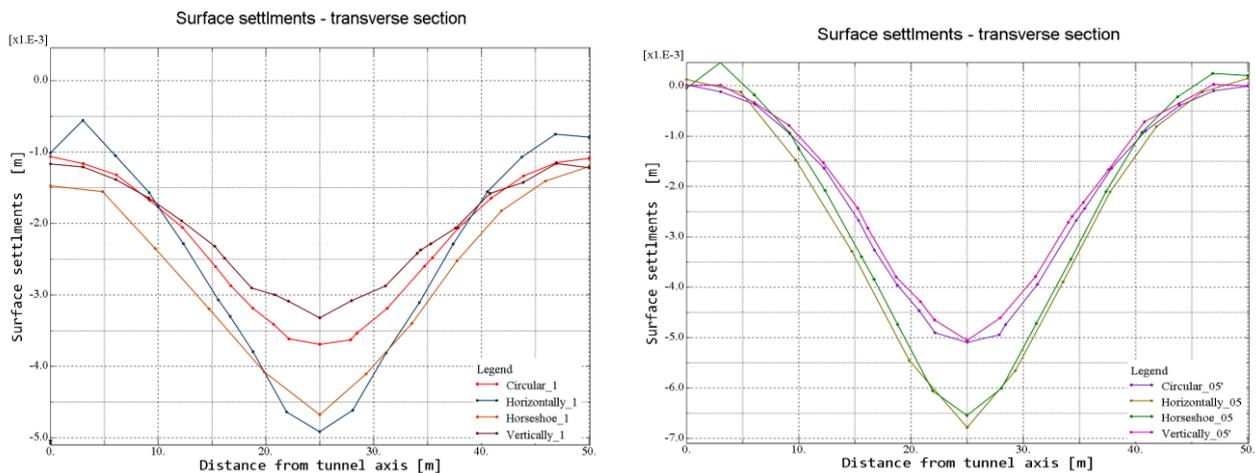


Figure 6. Surface settlements for analyses with  $k=1$  (left) and  $k=0.5$  (right)

It can be notice from the FEM output that a vertically ovoid shape of the tunnel shows lower values at the surface settlement. On the other hand the horizontal displacements are greater than the vertical ones for this specific cross section. In the case where the surface settlement is of a significant importance the settlements should be limited as much as possible. As a conclusion, the vertically ovoid shape appears to be best option when the in situ stresses are equal.

In order to asses and to see how much the  $k$  value influences the surface settlements for different cross section, another set of analysis where develop with a value for the  $k$  equal to 0.5 fig. (6) right. When  $k$  equals 0.5 it means that the vertical stress is twice with regard to the horizontal one.

In this specific case higher values are obtained for the surface settlements, as expected, since the vertical stress is higher. The difference in settlement for the two different cross sections: circular and vertically ovoid is not that significant as the previous presented case. Maximum surface settlements of approximate 6.5 mm are obtained for the horizontally ovoid shape case and values of approximate 5 mm for the vertically ovoid and circular cross section are observed.

The following plot permits a better view of the surface settlements that occurred for all different cross sections that were studied for different k values.

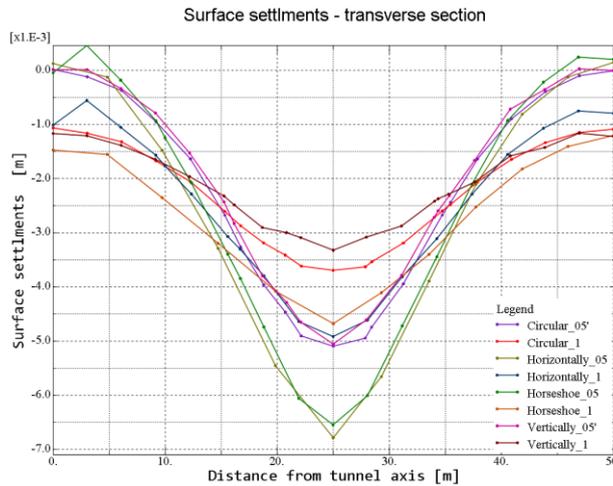


Figure 7. Surface settlements for analyses with k=1 and k=0.5.

For all analyses with k=1 it can be noticed that the settlement trough of the Gaussian curve is wide, whereas in the case of k=0.5 the settlement trough is narrow. In addition, in the former case it can be seen that the surface displacement start from a value of -1 mm, whereas for the latter one the Gaussian distribution curve begins from 0 mm. Moreover, where k=0.5 the vertical displacement between the circular and vertically ovoid shape are not that significant as in the former case.

Displacement vectors can be observed in fig. (8) for the circular case with k=1. The figure shows arrows whose length and orientation correspond to the vector displacement at each node. The dimensions of the vector plots are in the same range for all analyzed models. For this reason only one plot was used to present the magnitude of displacement vector size and orientation.

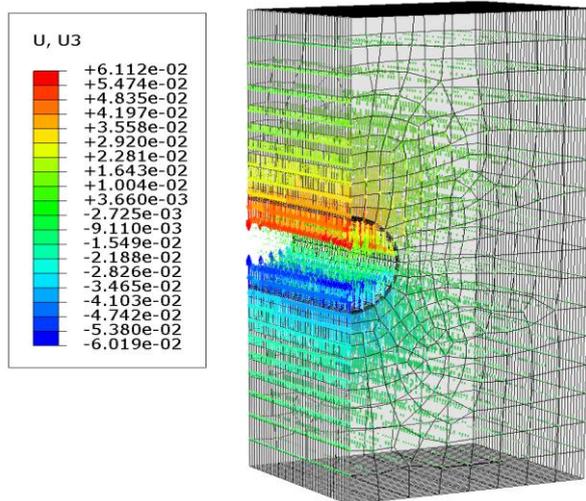


Figure 8. Displacement vector plot for u3, circular k=1.

The last graphic presents the surface settlement obtained from the empirical analyses. Both calculated values for the horizontal distance from the tunnel axis to the point of inflection of the settlement trough, are presented in the table 1. The value  $i$  was calculated using two different approaches see. Eq. (6) and Eq. (7). The differences are not significant, as a result the smallest value was chosen for calculation purposes.

Table 1: Input parameters for empirical calculation.

$r$ [m]	$Z_0$ [m]	$A_t$ [m <sup>2</sup> ]	GRL %	$V_s$ [m <sup>3</sup> ]	$K$ -	$i$ [m]	$i_1$ [m]	$i_2$ [m]	$i_3$ [m]	$i$ [m]	$S_{vmax}$ [m]
5	25	78.5	0.5	0.3925	0.5	12.5	12.49	12.5	13.26	12.75	0.0123

In contrast to the numerical calculation where different plots were presented for each analyzed cross sections in this case only one plot is allowed. The reason for this is that the empirical formulations cannot distinguish the shape of cross section, and it can take into account only the excavated area, which in our case is the same for all cross sections.

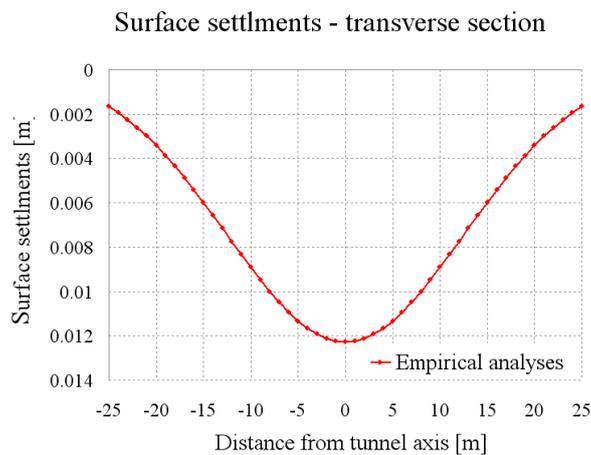


Figure 9. Surface settlements- Empirical formulation.

The empirical calculations reveal a higher value of the surface settlements in comparison with the finite element results. The empirical method cannot incorporate in the calculation the initial in situ stress, in contrast to the finite element method, where it can be observed that surface settlements are strongly dependent on the  $k$  value. Nevertheless, this calculation does not include the interaction between the soil and lining, therefore it cannot account for the stiffness's support. Normally the empirical method is used as a preliminary verification to get an idea about the displacement that will occur at the ground surface.

## 5. Conclusions and discussions

In the set of analysis where the vertical and respectively the horizontal stresses are equal, it was expected to see that the horizontally ovoid shape will induce the highest settlements at the ground surface. It is interesting to notice that the maximum settlement is almost 27% higher than the smallest surface settlement obtained in the case of the vertically ovoid shape. In this set of analysis with  $k=1$ , is to be pointed out that although in a regular basis a circular cross section will be preferred, the results obtained from the finite element method reveal that the vertically ovoid shape induces the smallest settlements at the ground surface. This is of higher interest, in the case where the settlements at the surface have an imposed restriction within the range of some millimeters. It

can be observed from the plot that in the case of the vertically ovoid shape the surface settlements are approximately 12% smaller in comparison to the circular cross section. The analyzed models are developed good soil conditions, and no stabilization or improvement methods were used. Nevertheless, the behavior of this two specific cross section is expected to follow the same pattern in terms of surface settlements, in other soil conditions than the one used in this paper. The  $k$  value strongly influences the shape and the magnitude of the transverse settlement profile.

The finite element calculations show a smaller value of the surface settlements with regard to the empirical one. The difference between the two is approximate in 41%. The empirical methods provide simplified estimations for the surface settlements induced by the tunneling excavation, but they are useful as a preliminary estimation, since the finite element method is a time dependent calculation.

This work suggests that the geometry of the cross sections appears to be a dominant factor for the surface settlement. This aspect hasn't been studied before; therefore further research should be done in this direction for a clearer interpretation.

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