Numerical Modelling of Tunnel Induced Settlement Using Plaxis

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***Abstract*—Due to increasing computing capacities over the past years the use of 3D Finite element analysis in underground design has become more common. Nevertheless, 3D calculations are time consuming and the necessary numerical tools may not always be available. In engineering practice empirical methods and 2D Finite Element analysis are used for tunnel design. The development of stresses and deformations due to tunnelling, however, is a complex three-dimensional problem. Reliable approximations are necessary. In this paper, tunnel induced settlements and internal lining forces are investigated for a non-circular tunnel in clay-/siltstone. The tunnel is constructed according to the principles of the New Austrian Tunnelling Method. 3D FE-analyses are compared with frequently used empirical methods and 2D FE-analyses. To account for three-dimensional stress redistribution in 2D the stress reduction method is used. Different reference values, constitutive models and stiffness parameters are compared. The obtained values are mainly influenced by the used reference value, ground water conditions and drainage type. Furthermore, the initial stress state and the soil model are shown to have an impact on the load reduction factor.**

***Index Terms*—Plaxis 2D, Lining forces, Constitutive models, New Austrian Tunnelling Method.**

I. INTRODUCTION

In tunnel design the stability of the ground, along with surface settlements, deformations of the cavity and the resulting forces on the lining are of main interest. The development of stresses and deformations is a complex three-dimensional problem. However, in engineering practice commonly simple empirical methods and 2D FE- analyses are used. To account for the effects of three-dimensional stress-redistribution in 2D calculations approximation methods have been developed. Conventional tunnelling is often referred to as sprayed concrete method or New Austrian Tunnelling Method (NATM). The support can be adjusted to current ground conditions. Therefore, its use is very flexible. Over the last years the use of conventional tunnelling techniques in hard soil/soft rock (HSSR) increased. The most common approximation method for modelling conventional tunnelling in 2D FE analysis is the stress-reduction method. In this paper, numerical calculations for a non-circular tunnel constructed in hard soil/soft rock using NATM are carried out with the commercial Finite Element code "PLAXIS 2D" and "PLAXIS 3D". The results of the 3D calculations are compared to the suggested approximation procedure in 2D, empirical methods and field data.

II. NUMERICAL MODEL

The exploratory tunnel Mitterpichling is part of the investigation program for the Koralm tunnel. It is constructed as the top heading of the later to be built south tube of the final project using the New Austrian Tunnelling Method (NATM). The tunnel cross-section is non-circular with an average area of 48 m².

The dimensions of the numerical model in PLAXIS 3D 2011 are chosen according to recommendations of the Committee on Numerical Methods in Geotechnics of the German Geotechnical Society "*Numerik in der Geotechnik*" to avoid the influence of boundary conditions:

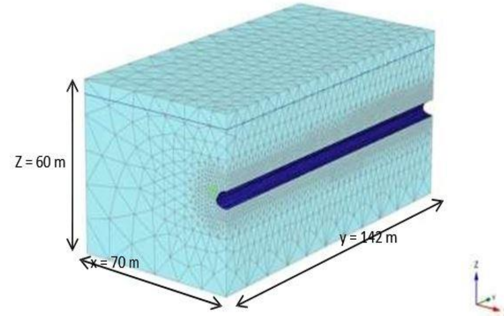

Fig.1 Numerical Model

III. GROUND CONDITIONS

For numerical calculations the tunnel section between station 1016 and 1187.5 of the exploratory tunnel Mitterpichling Ost is chosen. It can be considered as more or less homogeneous with dominant rock type silt- and clay stone, slightly consolidated. The ground was previously loaded by a 25 m thick soil layer resulting in 500 kN/m² pre-overburden pressure. The groundwater table is about 5 m beneath the surface. The overburden in this section increases from 22.5 meters to 27.5 meters. Therefore, the considered average overburden is about 25 meters above the tunnel crown. The tunnel is supported by a 20 cm thick layer of shotcrete and anchors. No pipe roof is needed to secure the tunnel face. In the considered section tunnelling was carried out conventionally using blasting and excavators. The length of advance is between 1.3 and 1.7 m.

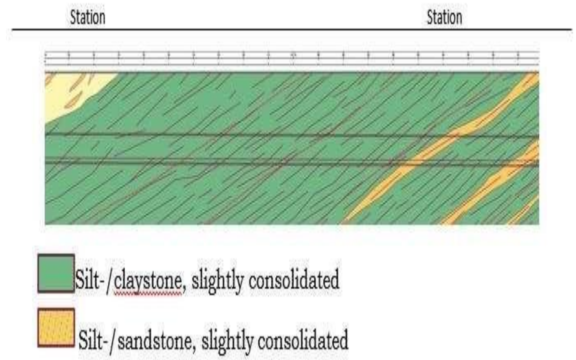

Fig.2 Geological Profile

IV. SOIL PARAMETERS

No material parameters were available for the considered tunnel section. Hence, data from the adjoining construction lot Paierdorf for the same geological unit are adapted as furnished in Table 1.

TABLE 1: Material Parameters

γ [kN/m³]	E [MN/m²]	ν	c [kN/m²]	[°]	K_0 [-]	Depth z	m [-]
21.5	270	0.2	35	27	0.54	70	0.8

In the first step the stiffness in 70 meter depth is adjusted for the Mohr-Coulomb model to the level of the tunnel axis z= 30.0 m. In a second step reference stiffness parameters for the advanced Hardening Soil and HS-small models are back calculated from the stiffness in 70 meter depth. For the Hardening Soil and HS-small model a pre-overburden of 500 kN/m² is considered. The Hardening Soil-small model takes the higher initial stiffness of the soil at very small strains into account.

IV. MESH GENERATION

The generated mesh consists of 112585 soil elements, 1559789 nodes and has an average element size of 2.302 m. The generated mesh consists of 615 soil elements with an average element size of 2.613 m. The global coarseness is chosen as coarse (*nc* = 50) to fit the average element size of the 3D calculation. Around the tunnel the mesh is refined locally by a factor of 0.5. The minimum mesh quality is 0.312.

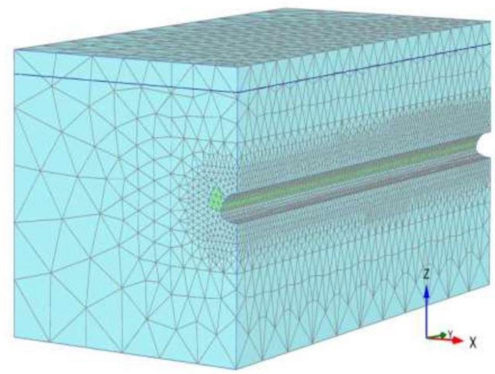

Fig.3 3D Finite Element Mesh

V. DRAINED 3D CALCULATIONS

Drained analyses are performed without consideration of groundwater conditions due to insufficient ground stability. To overcome boundary conditions a 20 m “ wished-in-place” section is inserted at the beginning and the end of the model. Surface settlements are evaluated after completed tunnel construction in two nodes in the middle of the FE- model above the tunnel centre-line. -Node 1: 0.0/71.0/0.0 & Node 2:0.0/74.23/0.0. The vertical settlements obtained from the three-dimensional numerical calculations are summarized in Table 2. In the middle of the FE-model steady state surface settlements are obtained. The largest deformations are predicted with the lowest stiffness parameters *EMC* = *Eur*. Settlements calculated with the Hardening Soil model exceed the results of the corresponding HS-small model. The initial stress state has a significant influence on surface settlements.

TABLE 2: Surface Settlements from Drained FE-Analysis

	Eoed, ref [MN/m²]	E50, ref [MN/m²]	Eur, ref [MN/m²]	station	
				71.00 m	74.23 m
1) MC	E=135 MN/m²			-15 mm	-15 mm
2A) HS E45				-11 mm	-11 mm
2B) HS E45	45	45	135	-7 mm	-7 mm
2C) HS E45				-16 mm	-16 mm
3) HS E20	20	20	60	-23 mm	-23 mm
7) HSS E45	45	45	135	-5 mm	-5 mm
9) HSS E20	20	20	60	-11 mm	-11 mm

The corresponding transversal settlement troughs in Station y = 71.0 m are displayed in Figure 4. They are compared to field measurements at station MQ 1015, 1040, 1067 and 1146.

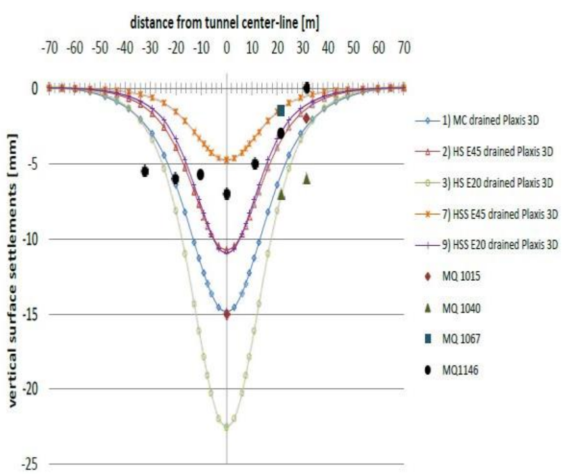

Fig.4 Comparison of the Transversal Surface Settlement Trough at Station 1015, 1040, 1067 and 1146 with the Results of the Numerical Drained Calculations in Station 71.

In Figure 5 the longitudinal settlement profile for station 71.0 m over the position of the advancing tunnel face is displayed. It is compared to field measurements in station 1015 and 1146.

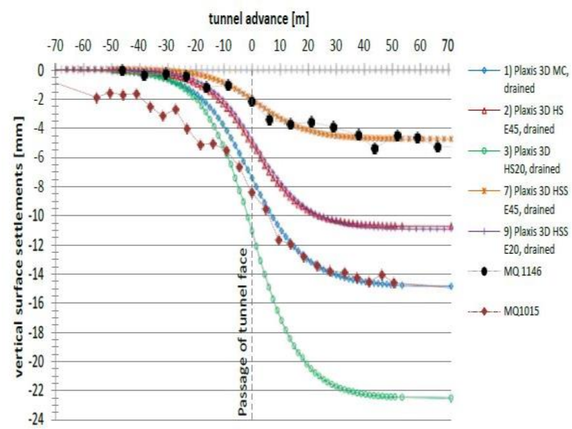

Fig.5 Comparison of the Development of Surface Settlements at Station 1015 and 1146 with the Results of the Numerical Drained Calculations in Station 71.

V. UNDRAINED 3D CALCULATIONS

Surface settlements are evaluated after completed tunnel construction in two nodes in the middle of the FE- model above the tunnel centre-line. - Node 1: 0.0/71.0/0.0. and Node 2: 0.0/74.23/0.0. The vertical settlements obtained from the three-dimensional numerical calculations are summarized in Table 3.

TABLE 3: Surface Settlements from Un-Drained FE-Analysis

	Eoed,ref [MN/m²]	E50,ref [MN/m²]	Eur,ref [MN/m²]	Station position	
				71.00 m	74.23 m
4) HS E69	69	69	208	-8 mm	-8 mm
5) HS E30	30	30	90	-16 mm	-16 mm
6) MC	E=135 MN/m²			-12 mm	-12 mm
8) HSS E69	69	69	208	-4 mm	-4 mm
10) HSS E30	30	30	90	-11 mm	-11 mm

Settlements obtained from undrained analysis are generally smaller compared to the results of the corresponding drained analysis. The soil stiffness parameters have a significant influence on the magnitude of surface settlements. The corresponding transversal settlement troughs in Station y = 71.0 m are displayed in Figure 6. The numerical results are compared to field measurements at station MQ 1015, 1040, 1067 and 1146.

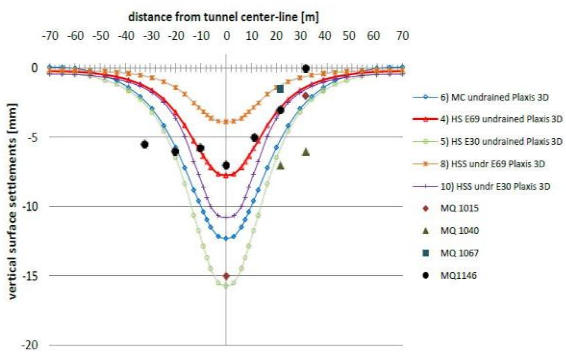

Fig.6 Comparison of the Transversal Surface Settlement Trough at Station 1040, 1067 and 1146 with the Results of the Numerical Undrained Calculations in Station 71.

Settlements calculated in undrained analysis are generally smaller than the deformations obtained from comparable drained analysis. Settlements obtained from calculations using the standard Hardening Soil model are 2.4-times larger than corresponding deformations computed with the HS- small model. The influence of small-strain stiffness is approximately the same for crown and surface settlements. In Figure 7 the longitudinal settlement profile for station 71.0 m over the position of the advancing tunnel face is displayed. It is compared to field measurements in station 1015 and 1146.

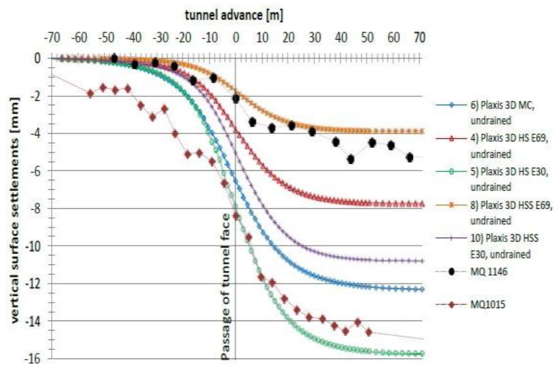

Fig.7 Comparison of the Development of Surface Settlements at Station 1015 and 1146 with the Results of the Numerical Undrained Calculations in Station 71.

VI. COMPARISON WITH ANALYTICAL METHODS

The construction of a tunnel in soft rock/hard soil inevitably causes ground movements. Depending on the construction techniques different support measures are installed to guarantee the stability of the cavity and reduce deformations. The surface settlement profiles obtained from 3D and 2D FE-analysis are compared to the probability functions of the empirical method Peck (1969). Field data for the development of surface settlements during tunnel construction show a large range in the evaluated section. Hence, a comparison with the results of empirical and FE analysis is not realistic. The tunnel face passes the considered measuring cross-section MQ 1015 on the 25.10.2005 and MQ 1146 on the 16.11.2005. In the figures 8 & 9 the surface settlement trough developed at the time of passage of the tunnel face as well as the settlements at the respective station for the position of the advancing face are displayed.

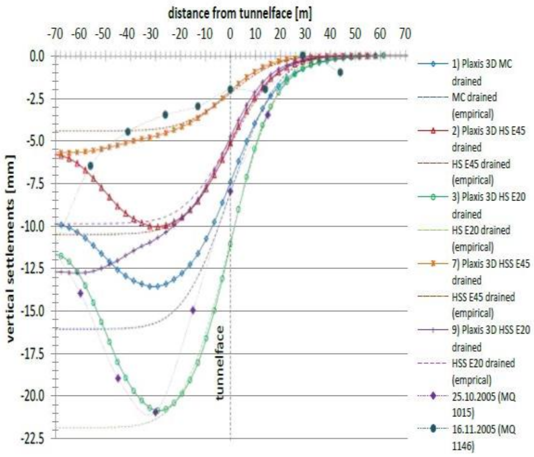

Fig.8 Longitudinal Surface Settlement Trough for Drained Analysis.

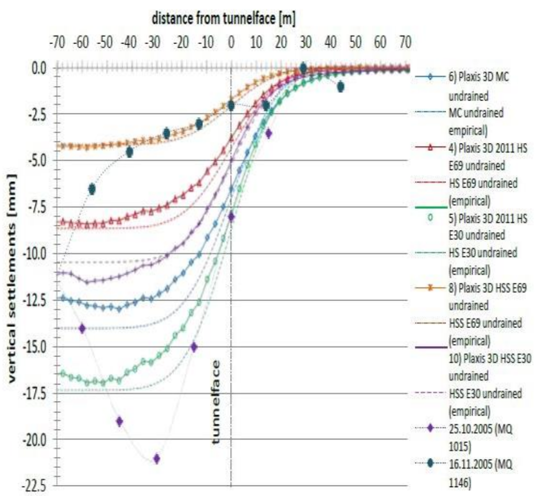

Fig.9 Longitudinal Surface Settlement Trough for Undrained Analysis.

The influence of the initial stress distribution on the development of the longitudinal settlement trough corresponds to the influence on the transversal settlement profile. For undrained analyses the cumulative probability curves are a better fit to the longitudinal surface settlement profile in 3D due to sequential excavation also at the tunnel start.

VII. CONCLUSIONS

The objective of this Paper is assessment of tunnel induced settlements. The influence of different reference values, constitutive models and the initial stress state was of main interest. The investigated tunnel "*Mitterpichling Ost*" is an exploratory tunnel with a non-circular cross section. It is excavated as the top heading of the final tunnel using the New Austrian Tunnelling Method. Although ground conditions were assumed homogenous, field measurements of deformations showed a wide scatter. All used soil parameter sets predict settlements within the measured range. It is concluded that in reality ground conditions are inhomogeneous and/or the behaviour is influenced by stratification and discontinuities. Surface settlements obtained from Finite Element analysis are in good agreement with the empirical distribution by Peck (1969).

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