COMPUTATION OF LABORATORY TEST RESULTS TO ESTIMATE THE LOSS OF AIR IN COMPRESSED AIR TUNNELLING

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ABSTRACT

Compressed air in combination with NATM is a technique to prevent water inflow during tunnelling construction. Under certain conditions, this technique is an appropriate method in tunnelling below ground water table in soils in urban areas. However, the amount of air loss is the major factor to consider when using this technique. In order to gain more accuracy in predicting the amount of air loss, large scale tests were performed in the laboratory of the Institute for Soil Mechanics and Foundation Engineering at Graz University of Technology. Meanwhile, a numerical simulation of this laboratory test was modelled using the software code TOUGH2. Agreements between measured results and computational results were found. The results of the numerical simulation are discussed in this paper. An outlook on future research work will be given.

INTRODUCTION

Using NATM in combination with compressed air the appropriate pressure is calculated as shown in Figure 1.
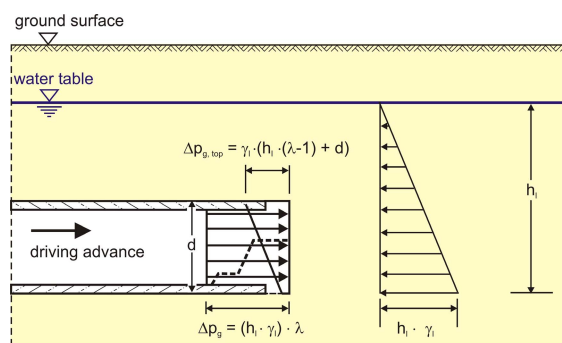

Figure 1. Compressed air to prevent ground water inflow.

Because of a disequilibrium between air and water pressure at top of the tunnel, air flows into the soil. This phenomenon causes air loss during compressed air tunnelling. Subsequently the soil which is initially fully saturated becomes unsaturated.

To estimate the correct amount of air flow into the soil the theoretical approaches of unsaturated soils and the flow of two immiscible fluids in porous media have to be considered.

To keep the air pressure at a certain level, the amount of air loss into the soil must be compensated by a compressor station. The amount of air loss is the major factor to consider when using this technique. Tunnelling engineers currently estimate it from empirical formulae. For this reason, various theoretical approach to the flow of air and water in tunnel construction using compressed air based on numerical models have been presented for example by Gülzow (1994) and Hochgürtel (1998), Javadi & Snee (2002), Perau (1999) and Oettl et al. (2002).

Research work has been done at the Institute for Soil Mechanics and Foundation Engineering of Graz University of Technology to enhance the capability of numerical models in compressed air tunnelling. Kammerer (2000) analyzed the behaviour of air flow through a cracked shotcrete lining into the soil behind the lining. An extension of the measuring program was performed by Scheid (2000) and Semprich & Scheid (2002). An approach to numerical model was studied by Scheid & Semprich (2002). As a consequence, an assessment for numerical models was performed. Comparisons between measurements and computations are presented. Strain measurements showing soil deformation due to two phase flow are presented and discussed.

LABORATORY TESTS AND RESULTS

A large scale laboratory testing apparatus to measure the flow of air through a cracked shotcrete lining into soil was developed. Figure 2 shows the testing apparatus to estimate the correct amount of air flow into the soil.

A container of dimension $1000 \times 900 \times 894$ mm was installed on top of shotcrete lining. A crack was developed at the center of the lining. The soil was installed in thin layers with approximately optimum water content and compacted at proctor energy. A pressure chamber was installed air tight below the shotcrete lining. After preparing the soil, a screen was installed on top of the soil where the air could escape freely. On top of the screen a load was applied to simulate overburden pressure of the soil above the tunnel. Strain gauges were installed on the vertical

tension rods to measure their deformation. The deformation of the soil due to air flow was measured via these strain gauges.
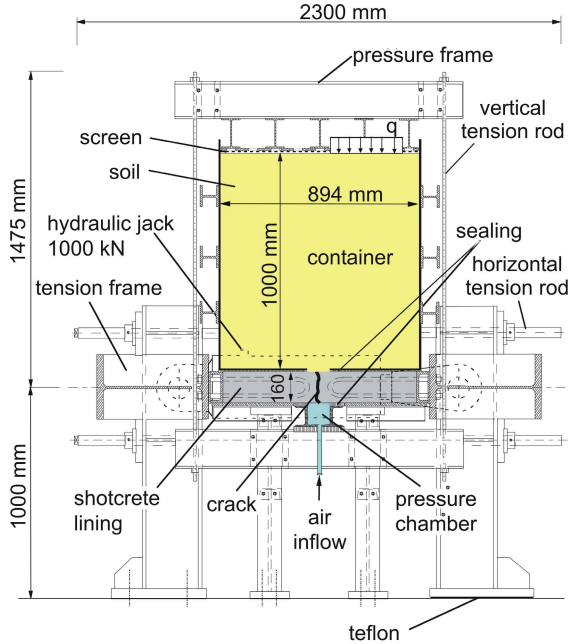

Figure 2. Laboratory testing apparatus

Within the soil, instruments including twelve pressure sensors, eight TDR probes and eight tensiometer probes were installed symmetrically. An installation plan of these sensors is shown in Figure 3.
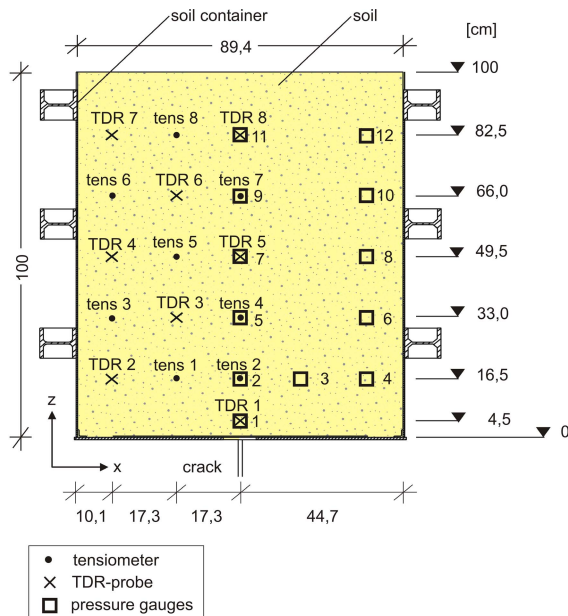

Figure 3. Installation of pressure gauges, TDR-probes and tensiometers.

The crack width was measured by means of fissure-meters. Equipments including thermometers, barometers and hydrometers, were used to determine and control laboratory conditions.

Prior to testing, the soil was permeated with water from top down. After reaching maximum saturation, compressed air was applied to the pressure chamber and flowed through the crack into the soil. The amount of air flow was measured by glass tube volumetric flow meter before entering into the pressure chamber. The characteristics of the flow in the soil and its influences including air pressure, water saturation and capillary pressure were monitored.

Particularly, the pressure level of the air, the width of the cracks in the shotcrete lining, the thickness of shotcrete lining and the type of soil were varied. In the tests described in this paper silty sand, common for compressed air application, was used. Characteristics of the soil are given in Table 1.

Table 1. Characteristics of chosen silty sand.

a) Characteristics of the silty sand		
grain size distribution	clay	4%
	silt	23%
	sand	71%
	gravel	2%
effective grain size	d_{10}	0.01 mm
coefficient of uniformity	U	18
specific gravity of soil grains	G_s	2,67
b) Characteristics of the compacted soil		
dry density	ρ_d	1.77 g/cm^3
porosity	n	0.34
void ratio	e	0.5
coefficient of water permeability	k_l	$4 \cdot 10^{-7}$ m/s

Laboratory test results for a cracked shotcrete lining of 0.3 mm width with an air pressure of 500 mbar are shown in Figures 4, 5 and 6.

The amount of air flow measured in the laboratory is shown in Figure 4. Results show that immediately after test initiation, the amount of air flow of $Q_g = 15$ m^3/h was measured. The amount of air flow gradually increased with time and reached an approximately steady state value of $Q_g = 30$ m^3/h after six days.

Measurements of the water saturation are given in Figure 5. The water saturation decreased with time and reached a steady state condition approximately

12 hours after beginning the test. Two measuring points are identified in Figure 7.
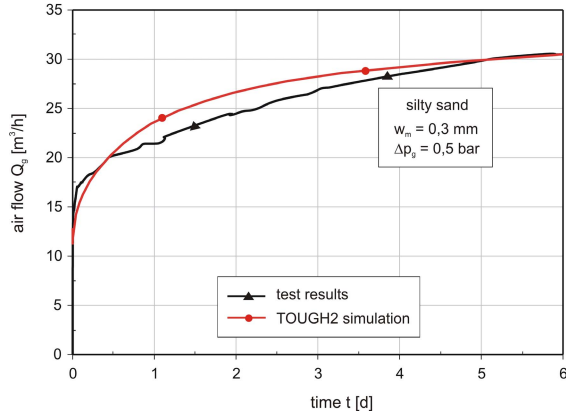

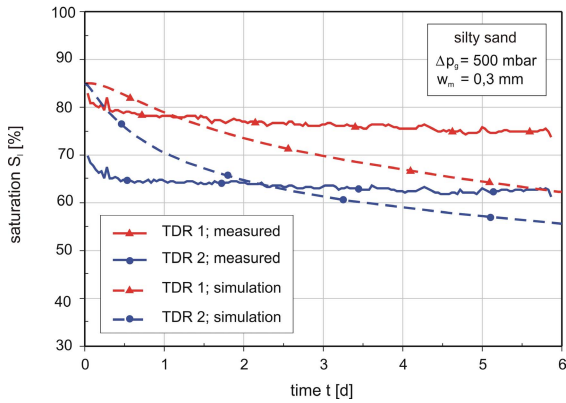*Figure 4.   Air flow from laboratory test and computation.*

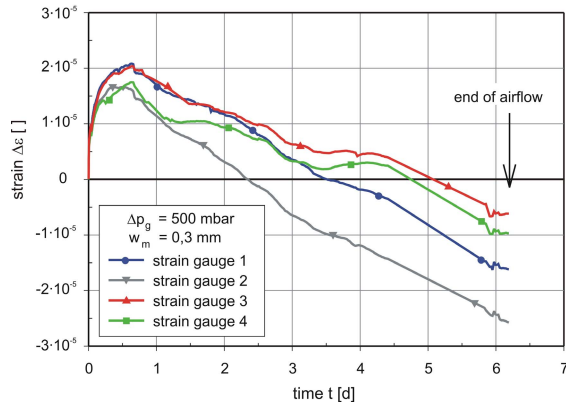*Figure 5.   Water saturation from laboratory test and computation.*

Figure 6.   Strain of vertical tension rods versus time.

Figure 6 shows the strains of the vertical tension rods. Deformation characteristics of the soil in the container can be interpreted from these strains. Re-

sults show that the soil experienced heaving in early stage followed by settlement after approximately 3 days. Possible arguments for this phenomenon are discussed in the conclusion.

NUMERICAL SIMULATION

The laboratory test was simulated numerically with TOUGH2 (Pruess et al. 1999) using the EOS3 module. The soil with the characteristics described in Table 1 was modeled using a two-dimensional Finite Difference grid as shown in Figure 7.
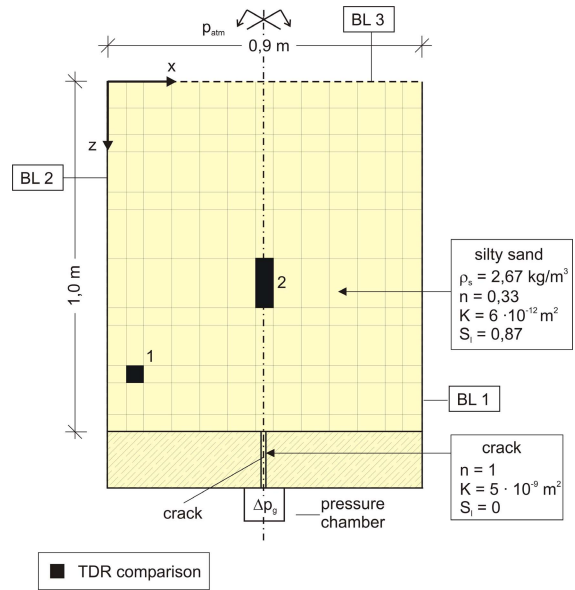

Figure 7.   Numerical model of the laboratory test.

The Finite Difference grid and the boundary conditions can be seen in Figure 7. BL1 and BL2 are impermeable boundaries whereas BL3 is of free-flow boundary type. These boundaries are described as follows

$$Q_g, Q_l = 0 \qquad \text{for BL1 and BL2}$$

$$\left.\begin{array}{l} Q_g, Q_l \neq 0 \\ P_g = const = P_{atm} \\ P_l = const \end{array}\right\} \qquad \text{for BL3}$$

The cracked shotcrete lining with characteristics shown in the Figure 7 was modeled as a continuum element. An air pressure at a level of 500 mbar was prescribed in the pressure chamber.

The capillary pressure was predicted by the model proposed by van Genuchten (1980)

$$P_c = -P_o \left(\left[S_e\right]^{-1/\lambda} - 1\right)^{1-\lambda} \qquad (1)$$

Here S_e is effective water saturation which is defined as

$$S_e = \frac{S_l - S_{rl}}{S_{sl} - S_{rl}} \qquad (2)$$

The capillary pressure P_c is restricted to

$$-P_{\max} \le P_c \le 0 \qquad (3)$$

Definition of parameters and their values used in the model are expressed in Table 2.

Table 2. Parameters used in van Genuchten capillary pressure.

Parameter	Definition	Par. value
S_{rl}	residual water saturation	0.01
S_{sl}	water saturation at full saturation	0.95
λ	curve fitting parameter	0.25
$1/P_o$	curve fitting parameter	0.0012 [1/Pa]
$P_{\max}$	maximum capillary pressure	$1 \cdot 10^{-7}$ [Pa]

The relative permeabilities for gas and liquid phases were predicted by the model based on two-phase flow of stream and water proposed by Verma et al. (1985)

$$k_{rl} = S_e^{\,3} \qquad (4)$$

$$k_{rg} = A + BS_e + CS_e^{\,2} \qquad (5)$$

Here S_e is effective water saturation as defined in van Genuchten capillary model. However, the parameter values used to calculate S_e were different. Table 3 gives the definition of parameters and their values used in the model.

Table 3. Parameters used in relative permeability model proposed by Verma et al. (1985).

Parameter	Definition	Par. Value
S_{rl}	residual water saturation	0.40
S_{sl}	water saturation at full saturation	4.00
A	curve fitting parameter A	1.30
B	curve fitting parameter B	-9.00
C	curve fitting parameter C	5.00

It should be mentioned here that these parameters are empirical parameters that have been used to fit the measurement of air flow.

COMPARISONS

Figure 4 shows comparison between measurements and computations of the amount of air flow. The comparison shows very good agreement. A slightly overestimation of computation was observed during 0.5 to 5 days. The computation, however, reached the same value as the measurement afterward.

Figure 5 presents the water saturation measurement and computation saturation. Comparisons between the measurements and computations are considered satisfactory. However, the water saturation measurement decreased faster than the computations.

Finally, the air pressures in the soil were compared. Distribution of air pressure measurements and computations are shown in Figure 8. Symmetric conditions for the measurements were assumed. As an example a situation after 12 hours is represented. Good agreement in distribution of air pressure can be found in the lower part of the container.
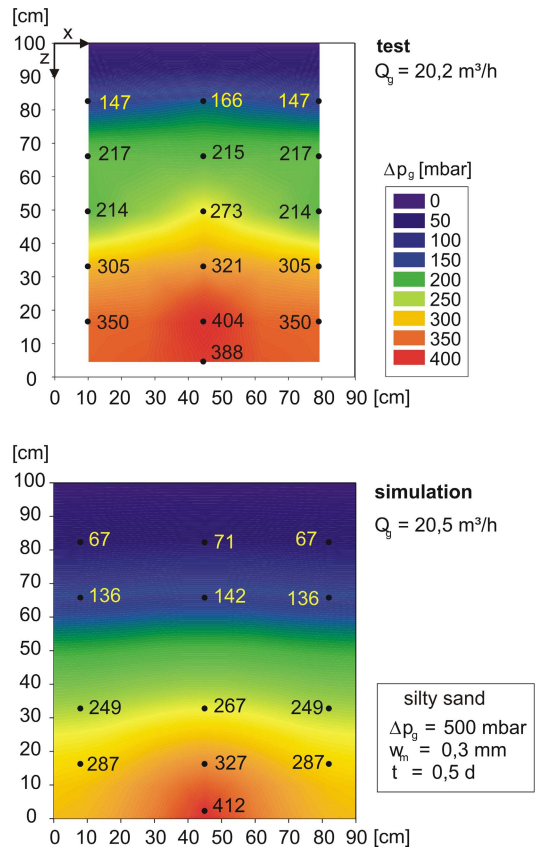
Figure 8. Air pressure distribution.

CONCLUSIONS

Simulation of two phase flow in compressed air tunnelling with TOUGH2 using the EOS3 module has been performed. Implementation of numerical simulation for air flow through the cracked shotcrete lining and adjacent soil in laboratory was performed and compared with the laboratory results. Comparisons show that the numerical model captures the air flow in the laboratory tests very well both in magnitude and variation. According to the agreement, numerical computation of air flow in tunnel advance is now being analyzed.

Improvement, however, could be considered for the air pressures and the water saturation. Further studies to improve the agreement between the measured values and the simulation might be categorized into laboratory research and computational works.

Regarding to the laboratory research work, investigating the parameters of the capillary pressure function and the relative permeability function would improve the results.

As for the computational works, Figure 5 shows that initial water saturation state simulated in the computational model did not represent realistic initial water saturation in the laboratory. The initial water saturation state in the laboratory varied with depth whereas the initial water saturation state simulated in the model was assumed constant at value of 87%. The variation of water saturation in laboratory came from the gravitational downward flow of the pore water in the soil before beginning the test. This phenomenon was not taken into account in the numerical simulation. Moreover, it is worth mentioning here that porosity of the soil in the numerical model assumed constant over testing period which contradict reality. Under real conditions the deformation of the soil takes place during the test as shown in Figure 6. To enhance capability of the computation, the deformation of soil based on theoretical approaches of unsaturated soils should be added into the computation.

Followings are possible explanations of soil deformation due to air flow. At the beginning of the test there was only air flow into the soil whereas an amount of air flow out of the soil was zero. The difference between the amount of air flow into the soil and the amount of air flow out of the soil gradually decreased with time and reached zero at the steady state. As a consequence, heaving in the early stage was governed mainly by negative balance of the amount of air flow in and out of the soil. Another factor might influence heaving of the soil is buoyancy upward force due to flow of air. As the difference between the amounts of air flow in and out of the soil became smaller, major factors governed the deformation of

soil changed to the capillary pressure, which increased with time until a steady stage was reached, inducing settlement of the soil afterward. These arguments might be proved in further study where the deformation of soil will be added into the computation.

REFERENCES

van Genuchten, M. T., A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Science Society*, 44, 892-898, 1980.

Gülzow, H. G., Dreidimensionale Berechnung des Zweiphasenströmungsfeldes beim Tunnelvortrieb unter Druckluft in wassergesättigten Böden, *Veröffentlichungen des Instituts für Grundbau, Bodenmechanik, Felsmechanik und Verkehrswasserbau der RWTH Aachen*, Germany, 25, 1994.

Hochgürtel, T., Numerische Untersuchungen zur Beurteilung der Standsicherheit der Ortsbrust beim Einsatz von Druckluft zur Wasserhaltung im schildvorgetriebenen Tunnelbau, *Veröffentlichungen des Instituts für Grundbau, Bodenmechanik, Felsmechanik und Verkehrswasserbau der RWTH Aachen*, 32, 1998.

Javadi, A. A., and C. P. M. Snee, Numerical modeling of air losses in compressed air tunneling, *The international Journal of Geotechnics*, 2(4), 399-417, 2002.

Kammerer, G., Experimentelle Untersuchungen von Strömungsvorgängen in teilgesättigten Böden und Spritzbetonrissen im Hinblick auf den Einsatz von Druckluft im Tunnelbau, *Mitteilungshefte der Gruppe Geotechnik Graz*, Technische Universität Graz, 8, 2000.

Oettl, G., R. F. Stark, and G. Hofstetter, Numerical simulation of dewatering of soils by means of compressed air, *Proc. 2nd Int. Conf. Soil Structure Interaction in Urban Civil Engineering*, Zurich, Switzerland, 411-418, 2002.

Pruess, K., C. Oldenburg, and G. Moridis, *TOUGH2 User's Guide, Version 2.0*, Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, USA., 1999.

Perau, E., Flow of water and air in soils due to tunnelling under compressed air, Geotechnical Engineering for Transportation Infrastructure, *Proc. 12th Eu-*

rop. Conf. Soil Mechanics Geotechnical Engineering, 3, 2093-2099, 1999.

Scheid, Y., Die TDR-Methode zur Bestimmung des Sättigungsgrades teilgesättigter Böden, *Unsaturated Soils, Proc. 2ⁿᵈ Workshop*, Bauhaus-University Weimar, 4, 35-55, 2000.

Scheid, Y, and S. Semprich, Simulation of a laboratory test to analyse two-phase flow in compressed air tunnelling, *Unsaturated Soils, Proc. 4ᵗʰ Workshop*, Bauhaus-University Weimar, 8, 51-58, 2002.

Semprich, S., and Y. Scheid, Messprogramm für experimentelle Untersuchungen zum Tunnelbau unter Druckluft nach NATM, *Messen in der Geotechnik 2002, Proc. Institute for Foundation Engineering and Soil Mechanics*, Braunschweig University of Technology, 68, 303-320, 2002.

Verma, A. K., K. Pruess, C. F. Tsang, and P. A. Witherspoon, A study of two-phase concurrent flow of stream and water in an unconsolidated porous media, *Proc. 23ʳᵈ National Heat Transfer Conf.*, American Society of Mechanical Engineers, Denver, CO, 135-143, 1985.