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Assessing Air Loss during Compressed Air Tunnelling in Grouted Soils

S. Semprich, M. Lesnik & Y. Scheid
Institute for Soil Mechanics and Foundation Engineering, Graz University of Technology, Austria

ABSTRACT: In shallow tunnelling below the groundwater table compressed air can be used for preventing water inflow into the tunnel. Using this method air loss takes place through both the unsupported tunnel face and shrinkage cracks of the shotcrete lining. Until today it is very difficult to correctly estimate the amount of air loss during the design phase of a project, although this is a significant factor concerning the total construction costs of a tunnel. Furthermore, to reduce the air permeability of the soil, grouting techniques may be applied. At the geotechnical laboratory of the Institute for Soil Mechanics and Foundation Engineering in Graz large scale laboratory tests were conducted to simulate the air-permeability of the shotcrete lining and the soil. In this paper results of these tests are discussed and a method of calculation is presented to estimate the amount of air loss of a simulated tunnel advance. The presented example takes into consideration a grouted area around the tunnel.

1 INTRODUCTION

Compressed air in shallow tunnelling is used to counteract the tendency of water to flow into the opened space. The method of compressed air has gained new importance recently, because in urban areas it does not influence the surrounding groundwater. Another aspect is that the mobilization of existing contaminants into the direction of the tunnel can be prevented. Main advantages of tunnelling under compressed air are on the one side, that this method does not affect the aquifer, on the other side it reduces the settlements on the ground surface due to the upward acting force of the compressed air. One major disadvantage is that the excavation work takes place under severe conditions (Scheid et al. 2001). Depending on the soil conditions, the geometry of the tunnel and the applied air pressure the amount of air loss varies. Air loss takes place both through the unsupported tunnel face and shrinkage cracks of the shotcrete lining. The required air pressure must be controlled and adjusted if necessary continuously.

In order to reduce the air permeability of the adjacent soil grouting methods can be applied. This paper presents a tunnel using NATM in which compressed air and grouting of the soil are combined. The combination of both methods has been already applied successfully in metro tunnel projects in Duisburg/Germany (Weiler & Misch 1982) and in Munich/Germany (Kramer & Semprich 1989).

Figure 1. Longitudinal section of tunnel

In the chosen example the ground (Fig. 1) consists of a 2 m thick layer of fill at the top. Quaternary gravel reaching into a depth of 10 m below ground surface follows. Beneath the Quaternary sand, silt and clay layers of the Tertiary were investigated. The Quaternary is constituted of sandy gravel. The content of sand is varying widely (Fig. 2). Porosity is about $n = 25-30\%$. The water permeability is altering between $k_p = 1 \cdot 10^{-4}$ and $5 \cdot 10^{-2}$ m/s.

The change of the Quaternary and the Tertiary layers lies within the whole tunnel length at the level of the side wall. Furthermore, the Tertiary is of relative water impermeability. Ground water level was measured about 1 to 4 m above the tunnel crown.
Due to the relatively high permeability of the gravel a compressed air advance without additional grouting of the gravel is not economically. Therefore, the tunnel sections within the Quaternary and a 2 m thick neighbouring area will be injected with grouting material. By this measure the pores in the gravel are filled with grouting material reducing the permeability. The drillholes for the grouting work are executed from shafts located along the tunnel (Fig. 3).

A large-scale laboratory test was developed at the Institute for Soil Mechanics and Foundation Engineering of Graz University of Technology to simulate the air permeability of the shotcrete lining and the soil. Different parameters have been varied. These parameters were (1) the amount of air pressure, (2) the width of the cracks in the lining, (3) the thickness of the lining and (4) the soil type (Semprich & Scheid 2002b). Figure 5 shows the testing apparatus.
In the pressure chamber an overpressure of 0.1 to 2.0 bar was applied. The air flows through a crack of a 16 cm thick shotcrete lining into the soil. The crack has been carried out and its width has been fixed by the use of a hydraulic tension frame. The crack width varied from 0.1 mm to 0.7 mm. After passing the crack the air entered into the soil column with a height of 1 m. Additional experiments included different degrees of initial aqueous saturation and two types of soil, sand and silt. During the test the over pressure of the gaseous phase (air) \( \Delta p_g \) was measured in the pressure chamber and at different locations in the soil column. Additionally, the volumetric airflow \( Q_g \) based on standard conditions in the laboratory, the aqueous saturation \( S_a \) in the soil column, the overburden pressure \( q \) applied on top of the soil column and the temperature were measured.

The results of the test lead to an improved approach to describe the air permeability through the system of a cracked shotcrete lining and adjacent soil (Kammerer 2000):

\[
k_{g,S} = \frac{Q_g}{A \cdot \gamma_a} \cdot \frac{2 \cdot p_{atm} + \Delta p_g}{(2 \cdot p_{atm} + \Delta p_g) \cdot \Delta p_g} \quad (1)
\]

Equation is applied when estimating the amount of air needed for a tunnel project as presented in section 4.

Further tests with additional measurement devices were conducted in 2001 (Semprich & Scheid 2002b). They focused on the dependency of the air flow to the saturation of the soil. Results for sand in a dense condition are shown in Fig. 6.

Directly after applying the overpressure in the pressure chamber the volume of air flow was about \( Q_g = 15 \text{ m}^3/\text{h} \). The amount of air flow increased subsequently until it reached a steady-state level after \( t = 1.5 \text{ h} \). Until that time the amount of air flow doubled. Fig. 6 shows the dependency of degree of water saturation and air flow versus time. The degree of water saturation was measured with two TDR gauges (Scheid 2001, Roth et al. 1992). The lower gauge was installed in the centre of the box 33 cm above of the bottom of the soil container. The second gauge was situated 33 cm below of the top of the container, also in the centre of the box. Fig. 6 shows that water was removed from the container directly after applying the compressed air. The decreasing degree of water saturation was more important in the lower part of the container. After \( t = 0.5 \text{ h} \) nearly 25% of water was removed from the lower part of the box. At the end of the test \( (t = 4.5 \text{ h}) \) the degree of water saturation was reduced to \( S_a = 55\% \) in the lower part. As one can notice both water saturation curves intersect at \( t = 0.5 \text{ h} \). This is due to the upward orientation flow of the air and water phase. Similar to the amount of air flow the degree of water saturation reached a steady-state at the end of the test.

![Figure 6. Air flow and degree of water saturation versus time](image)

3 CONSIDERATIONS RELATED TO GROUTING WORKS

The results of the laboratory test described in section 2 show, that tunnelling compressed air leads to a high amount of air loss. Especially in a soil with a high permeability the construction method is not economic without measures to reduce the air permeability of the adjacent ground. These test results fit also to practical knowledge. Therefore, in the above mentioned example (Fig. 1 & 3) the tunnel sections within the Quaternary and a 2 m thick neighbouring area will be injected with grouting material. By this measure the pores in the gravel are filled with grouting material reducing the permeability.

The drillholes for the grouting works are executed from shafts located along the tunnel. They are situated fan-shaped with different lengths and inclinations, which may lead to complex geometries. It is usual to carry out drilling with lengths up to 30 m. According to the European Standard EN 12715 (Grouting Works) a maximum deviation of 3% of the drillhole length up to 20 m is permitted. Therefore either the accuracy of the drillings have to be increased, or the deviations have to be taken into account when designing the grouting measures. Recent developments have shown, that it should be possible to increase the accuracy up to 1,5% of the drilling length.

The installation of the grouted body is carried out by inserting the grouting material into the ground through sleeve tubes (tube à manchettes). The manchettes have defined distances and will be used one by one by applying a double-packer system.

Each grouting process lasts until one of two independent criterions to stop the grouting process is attained. The first criterion concerns the grouting
pressure, the other one the maximum amount of grouting volume, which is determined for each injection stage taking into account the distance to the adjacent drillings and the theoretical pore volume of the surrounding soil.

Beside considerations according to the deviations of the boreholes, following additional measures for quality control are recommended:

- Measurement and recording of parameters, such as flow rate, pressure, time of penetration and soil profile.
- Qualification tests of the grouting material with respect to environmental protection, viscosity and adaptation to the ground.
- Verification of the chosen injection method by carrying out field tests.
- Laboratory tests to determine strength and air permeability of the improved ground.

4 EXAMPLE OF A TUNNEL

Figures 1 and 3 show the tunnel used for the following calculation of air loss. The chosen situation is similar to a metro tunnel in Vienna, which is under construction using slurry shield tunnelling method. The total length of the tunnel is 435 m. The construction time of the tunnel is assumed to 87 d. The position of the tunnel face of tube one is assumed 5 m ahead of tube two.

Three independent influences were established to estimate the total amount of air loss in the tunnel (Fig. 7).

The amount of air flowing through air locks and open pipes was taken into account with a constant value of $Q_Z = 5$ m$^3$/min.

The air loss through the tunnel face $Q_0$ is a function of the air pressure $p_g$ in the tunnel, the depth of the tunnel, and the geological conditions at the tunnel face. Since the tunnel depth was increasing the air pressure was increasing too with the advance of the tunnel. At the beginning of the tunnel excavation most part of the cross section was in the Quaternary. This led to a higher amount of air loss in the first ten days of the tunnel advance, as one can see in Fig. 7.

The most sensitive task was to estimate the air loss through the shotcrete lining $Q_S$. The actual value is depending on the air pressure at the tunnel lining, which is a function of the position of the tunnel face, the depth of the tunnel, the excavated and supported tunnel section by shotcrete and the soil condition above of the lining. To solve the problem the tunnel was divided into 20 blocks, each 5 m long. Each block had to be considered separately at different locations of the tunnel advance. At the first day only one block was taken into account. At the end of the construction period every block was passed through. The air permeability of the shotcrete lining was calculated using the results of the laboratory test. For the air permeability of the system consisting of the crack and the first meter of adjacent grouted soil a value of $k_{gs} = 5 \cdot 10^{-5}$ m/s was considered, as presented in section 2.

![Figure 7. Air flow during tunnel advance of model tunnel](image)

The total amount of air loss is increasing every day. Figure 7 shows that the total amount of air loss is nearly completely represented by the flow through the shotcrete lining.

As a result of the present calculation the compressor station can be dimensioned more accurately. Furthermore, the need of air for each stage during the construction period can be foreseen and the costs could be estimated already during the design phase of a tunnel project.

CONCLUSION

The paper has shown, that compressed air tunnelling in combination with NATM is an appropriate method for tunnelling in urban areas. When applying this method the grain distribution curve, respectively the air permeability of the soil has to be considered. Soils with large pores are not strictly unsuitable for compressed air, but grouting measures have to be considered. An analysis of the cost effectiveness has to follow the analyses of technical feasibility. Large scale laboratory tests may be conducted to better estimate characteristic parameters for the grouted soil. Those tests can be executed in the forefront of a tunnel project and help to calculate the air losses as shown in this contribution.

Furthermore, this paper has presented a tunnel as an example with chosen geotechnical parameters that are common for soils in urban areas. In a recent
work it has been applied on a compressed air tunnel project in Germany and showed good agreement with measured air losses. The discussed method has been developed on the base of analytical relations and laboratory testing procedures. The results show that it will be possible to foresee the amount of air needed for a compressed air NATM project. This tool may help the designer to better estimate the cost of a project. At the present level it is used especially for research work. Further research work is done on the field of numerical modelling of multi-phase flow.

ACKNOWLEDGEMENTS

The Austrian Science Fund (FWF) generously supported this work.

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