The main principles of tunneling under compressed air

Les principes essentiels du creusement de tunnel sous air comprimé

D. Placzek

ELE Consulting Engineers, Erdbaulaboratorium Essen, Germany

ABSTRACT

Tunneling in soil under the groundwater-level requires the sure removal of groundwater under construction. Different methods are available and they have proved in practice. There is to differentiate between the sealing, lowering and the squeezing of groundwater. While the sealing and the lowering of the groundwater have to anticipate the tunneling , it is necessary to squeeze the groundwater under construction. Standard solutions for groundwater-squeezing are the application for the support of the heading face by fluid or air pressure.

In this paper the main principles of tunneling under compressed air will be described. Based on the calculation methods for air flow, air requirement and air pressure the experiences of the last twenty years are summarized. In this connection it will be shown that always an air flow is necessary and has to hold up. Finally important recommendations are developed, risks will be described, the handling instructions with compressed air under construction will be defined and the application limits are referred.

RÉSUMÉ

Le creusement de tunnel dans le sol sous le niveau de la nappe phréatique nécessite un retrait sécurisé de l'eau souterraine sous la construction. Différentes méthodes ayant fait leurs preuves dans la pratique sont disponibles. Il convient de différencier l'étanchement, la baisse et l'esquichage de l'eau souterraine. Alors que l'étanchement et la baisse de l'eau souterraine doivent être préliminaires au creusage de tunnel, il est nécessaire d'esquicher l'eau souterraine sous la construction. Des solutions standard pour l'esquichage de l'eau souterraine consistent à appliquer une pression de fluide ou d'air pour le support du front d'avancement.

Ce document décrit les principes essentiels du creusage de tunnel sous air comprimé. Basées sur les méthodes de calcul pour l'écoulement de l'air, le besoin d'air et la pression de l'air, les expériences des vingt dernières années sont résumées. En l'occurrence, il est démontré qu'un écoulement d'air est toujours nécessaire et doit rester maintenu. Enfin, d'importantes recommandations sont mentionnées, les risques sont décrits et des instructions de manipulation de l'air comprimé sous la construction sont définies, de même que les limites d'application.

Keywords : tunneling, compressed air, air flow, air leaks, air permeability, out-blow, stability of the heading face

1 INTRODUCTION

In the course of tunneling under groundwater, compressed air is used in various construction methods as an additional building measure in order to hold back the existing groundwater when other options have to be ruled out for technical, economic or environmental reasons. Besides shield tunneling, where it is used either for supporting the heading face or as an additional supporting medium for support fluid, pipe installation, where the entire headway can be kept under compressed air, the cut-and-cover construction method, in which the flow of groundwater into the excavation pit is prevented by compressed air within the protection of watertight excavation pit walls under a watertight lid located above the groundwater; the shotcrete construction method in particular is hard to imagine in modern tunneling without the use of compressed air.

Here, as tunnelling proceeds, the groundwater is displaced by maintaining a suitable level of excess air pressure in the working area. This air pressure, which is higher than the atmospheric pressure outside the tunnel, leads to an air flow which must not be interrupted (Figure 1 and Figure 2). If the air flow is interrupted, or if there is an accumulation of compressed air, the groundwater can no longer be displaced, resulting in an inrush of water, which may cause the heading face to become unstable.

In the following it will be shown under what marginal conditions tunneling under compressed air is possible, what determines air permeability, how the required air quantities can be calculated, what measures can be taken when high air losses are to be expected, what stability analyses have to be carried out and what risks exist despite all precautions.

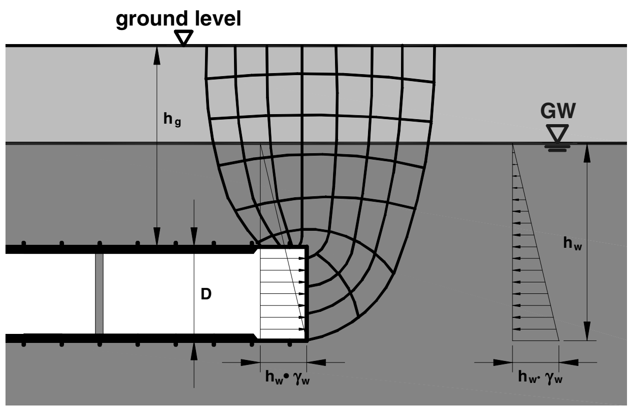

Figure 1. Air flow in a homogeneous soil during tunneling

M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-2465

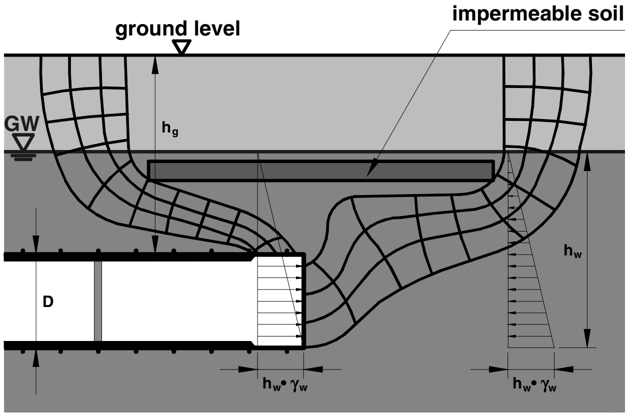

Figure 2. Air flow in an inhomogeneous soil during tunneling

2 BASIC CONDITIONS FOR THE EXECUTION

The use of compressed air in tunnel construction has become very widespread because it has many advantages in its favor:

a) safe control of the groundwater, since the necessary air pressure can be adjusted exactly to the hydrostatic pressure head of the groundwater table;
b) very easy to combine with other additional building measures;
c) only limited influence on the environment, since there is no appreciable change either in the hydrogeological conditions or in the chemical composition of the groundwater;
d) there is no surface subsidence triggered by a lowering of the groundwater level;
e) surface subsidence is partially reduced by the excess air pressure at the heading face.

A precondition for the use of compressed air is the permanent current of air during tunneling. Success is therefore largely dependent on air permeability, air flow and air pressure conditions.

Soils with a high level of permeability are suitable in principle, but the high air requirements represent a limit of applicability, unless the permeability of the subsoil is first reduced, for example with injections.(Figure 3).

In highly cohesive soil with very low permeability, displacement of the groundwater is generally not necessary, so that this can be regarded as a further limit of applicability (Figure 3).

Cohesive soil with intermittent deposits of permeable sand and gravel lenses cannot be controlled sufficiently safely with compressed air. In this case, if a lens is struck, the compressed air enters this lens, but cannot escape, which leads to the compressed air being trapped; as a consequence of this, water enters, leading to inevitable instability in the heading face.

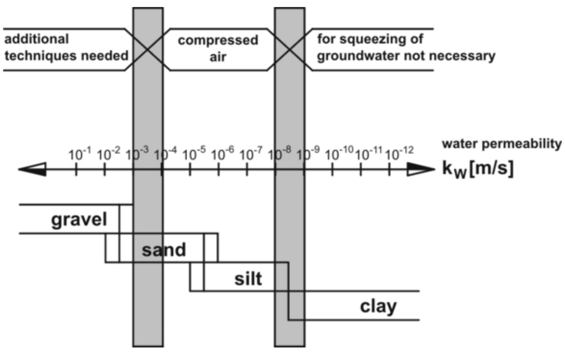

Figure 3. Limits of applicability (Schmidt & Seitz, 1998)

3 AIR PERMEABILITY

The quantity of air flow through the soil as a consequence of the difference in air pressure depends to a large extent on the air permeability of the soil. The air permeability of the soil expressed by the air permeability coefficient k_L can be determined by experimental means but is generally derived from the water permeability coefficient k_W. Here, the various permeability values are compared with the viscosity values and the air permeability coefficient is derived from this.

At a temperature of 10° C the ratio is 70, that is, the air permeability k_L is about 70 times greater than the water permeability k_W of the soil.

In–situ experiments have greater validity, since the determination of the subsoil data is more realistic here. Figure 4 shows the result of an in-situ experiment in Essen, Germany.

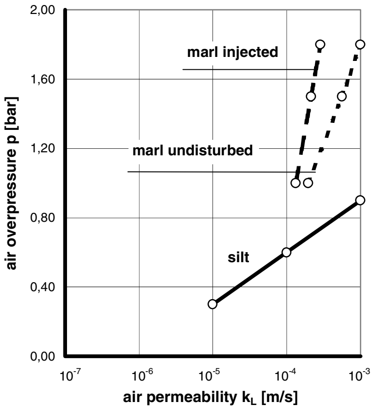

Figure 4. Results of an in-situ test for the determination of the air permeability in Essen, Germany (Kramer & Semprich, 1989)

4 REQUIRED VOLUME OF COMPRESSED AIR

According to Rieker (1992), the required volume of compressed air depends on many different factors. On the one hand it is dependent on the properties of the subsoil (including air permeability, layer thickness and layer sequence, homogeneity, erosion propensity), but on the other hand is also dependent on the design. Depending on the type of construction method used (conventional tunneling, shield tunneling), various air losses which influence the volume of compressed air required may occur here through the heading face or through the tunnel casing. The same applies for air losses occurring through scheduled locking operations or disturbances in the subsoil which can cause an unscheduled escape of air.

Consequently, a precondition for the determination of the required volume of compressed air is a dedicated examination of the flow field, taking account of hydrostatic conditions and a reliable assessment of possible air losses caused by the construction method used. The required volume of compressed air can then be calculated from

$$Q_L = Q_A + Q_M + Q_S \text{ [m³ / min]} \quad (1)$$

With
- Q_A Air loss through the heading face
- Q_M Air loss through the tunnel casing
- Q_S Air loss as a result of locking operations etc.

$$Q_A = C \cdot k_L \cdot A_O \cdot q_L \text{ [m³/min]} \quad (2)$$

Here, the factor C describes the spatial influence of the air flow field above the tunnel top. According to examinations carried out by Schenk (1961), this factor can be estimated to be 2 for covering heights of 1 to 2 D (D corresponds to the outer diameter of the tunnel) and largely homogeneous soil conditions. If the soil conditions are not homogeneous, higher factors must be taken into account, or suitable flow models in accordance with FEM must be examined (Gülzow & Wittke 1996 and 1997).

The air permeability coefficient k_L in m/min is to be determined experimentally or empirically. A_O in m² describes the area of the heading face.

The factor q_L corresponds to the influence of the pressure difference and the conversion of compressed into intake air in accordance with the Boyle – Mariott law. This is determined from the necessary air pressure p_T [bar] in the tunnel, h_g [m] the covering height, T (corresponding to h_w) the air pressure in the tunnel in m water column and D the outer diameter of the tunnel. In tunneling under compressed air in waterlogged soils, the factor q_L is thus generally determined from

$$q_L = \left(\frac{T}{\beta \cdot D} - \frac{1-\alpha}{\beta}\right) \cdot \left(\frac{P_T}{P_a} + 1\right) \tag{3}$$

In equation (3), the first factor describes the pressure difference in accordance with Figure 5 and the second factor the conversion from compressed into intake air.

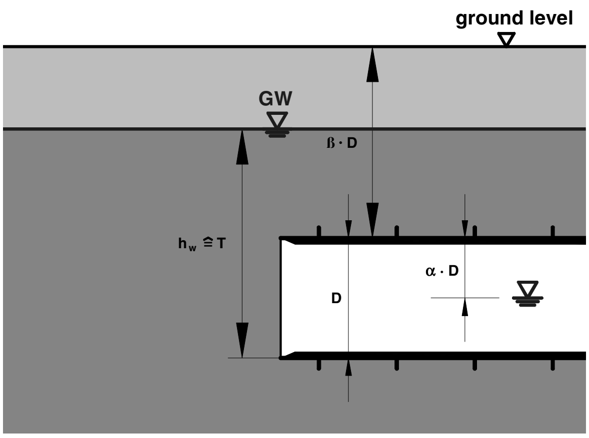

Figure 5. Terms for the calculation of the required air volume

At atmospheric air pressure of p_a = 1 bar, the factor q_L is then calculated as follows:

$$q_L = T/h_g\,(p_T + 1) \qquad [\text{m}^3/\text{min}] \tag{4}$$

In general, a distinction must be made between

- tunneling under compressed air in waterlogged soils and
- under open water.

Other marginal conditions remaining identical, the factor q_L under open water is determined by analogy from:

$$q_L = (D/h_g + 1) \cdot (p_T + 1) \quad [\text{m}^3 / \text{min}] \tag{5}$$

The air losses Q_M through the tunnel surface area, e.g. through the air permeability of the tunnel lining (shotcrete, tunnel joints, tail seal and the like) can be determined by analogy to equation (2) if instead of the air permeability coefficient of the soil the air permeability coefficient k_M of the tunnel surface area and the subsoil are inserted in m/min and the relevant tunnel surface area A_M is inserted:

$$Q_M = k_M \cdot A_M \cdot q_L \quad [\text{m}^3/\text{min}] \tag{6}$$

The air losses from locking operations and the like are dependent on the relevant conditions in each individual case, and must be laid down separately and taken into account in good time during the course of construction. According to experience gained so far, a volume of about 3 to 15 m³/min can be specified for locking operations.

The determination of the required volume of compressed air, which is decisive for the design of the compressed air system and thus for the safety of tunneling operations, should be effected with a significant safety margin, against the background of possible imponderables which cannot be accurately assessed in the calculation. For example, in the current project of the north-south city railway in Cologne, double the calculated quantity of compressed air was used as a basis for the compressed air system for both drives during the tunneling under compressed air under the Museum Ludwig near Cologne Cathedral.

5 FACILITIES FOR REDUCING AIR LEAKS

Besides the pressure, the quantity of air required determines the economic success of the measure. This applies particularly when tunnels have to be driven through highly permeable layers and the compressors reach the limits of their capacity. This also involves a safety risk which should not be underestimated.

To reduce air losses in the tunneling area, possible measures are soil injections made in advance of tunneling operations; these can lead to a significant reduction in air permeability. Air leaks can also be significantly reduced through skilful planning of excavation, for example by reducing the cross section of excavation.

In the region of the tunnel surface, a reduction of air leaks can be achieved if the shotcrete surface is sealed or the composition of the shotcrete itself is modified. A greater thickness of the shotcrete lining can help to reduce air leaks.

All of these measures must be taken into account in good time and evaluated in technical and economic terms, since they have an influence not only on the course of construction but also on the geometry of the excavation and on the environment.

6 STABILITY OF THE HEADING FACE

The air pressure acting during tunneling is generally adjusted to the level of the hydrostatic water pressure. The air flow, which is generally directed upwards in the direction of the atmosphere, is created by the air pressure, which acts uniformly on the heading face, being higher than the hydrostatically distributed water pressure at the top of the tunnel (air overpressure). This air pressure must be maintained permanently and must not be interrupted, even if this means an increase in air leaks.

If the air flow is interrupted by the sudden escaping of large quantities of air, this is described as an out-blow, which represents a failure and which must be prevented with sufficient reliability, for in the event of such an out-blow, which can be caused for example by a short circuit between the air pressure in the tunnel and the atmospheric pressure, the groundwater, which up to now has been held back, suddenly rushes in and leads to instability in the heading face, together with danger to life and limb of the miners and the infrastructure above.

However, this is not the only possible cause of an out-blow; higher air pressure in the tunnel top than the acting load from above can also lead to such a failure.

For safety against a possible out-blow, it must be proved that the load of soil and water acting on the tunnel top is sufficiently great compared with the acting air pressure (Figure 6).

Verification must be kept for all relevant cross sections and states of construction. In Germany, safety against out-blow must be verified with a global safety factor of at least η = 1.1. In justified cases, significantly higher safety levels may be required.

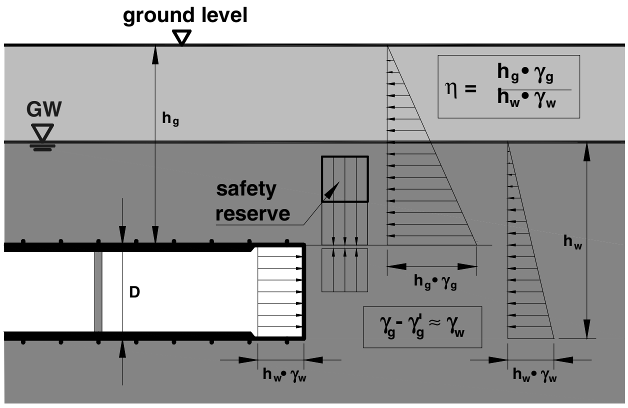

Figure 6. Safety against out-blow

$$\eta = h_g \cdot \gamma_g \;/\; h_w \cdot \gamma_w \tag{7}$$

On the safe side, the frictional forces in the soil counteracting the upward flow forces can be neglected in the verification of safety.

7 REMAINING RISKS

Work with compressed air may only be carried out by experienced personnel and with sufficient safety precautions. Even if many decades of practical experience are available, particular risks must be taken into consideration when working with compressed air.

Comprehensive and technically sound planning of the tunneling under compressed air is decisive, taking account of the limits of applicability (see above). Such planning includes a careful examination of the subsoil as well as groundwater monitoring, the calculation of the required quantity of compressed air, including an assessment of possible air leaks, and the selection of the technical equipment with an adequately dimensioned compressor system which does not reach the limits of its capacity even in the event of major air leaks.

Against the background that the air pressure in the tunnel must be maintained during the entire duration of the tunneling work, which can frequently last for several months, that the air pressure must constantly be adapted to the pressure conditions in the top of the tunnel as tunneling proceeds, and that the required volume of air is not inconsiderable, this type of construction involves particular risks, which must be examined carefully:

- health risks for the miners who have to work under compressed air
- risks arising from increased fire risk
- risks arising from a sudden breakdown of the air flow
- accumulation of compressed air

As a consequence of working under compressed air, which is understood to mean that persons are working at a pressure which is at least 0.1 bar, and at most 3.6 bar higher than atmospheric pressure, illnesses may occur (compressed air sickness). For this reason, the duration of working and the age of the miners is limited, in accordance with the safety regulations applicable in Germany. Instructions and precautionary measures are to be integrated in the work plan and complied with during execution.

Under increased air pressure, the fire risk in the tunnel is significantly higher than under atmospheric conditions. Inflammable materials can thus ignite more easily as a result of the higher oxygen content.

Working under compressed air requires a permanent air flow. An out-blow leads to sudden failure, since the sudden inrush of water can endanger life and limb of the miners, also taking into consideration possible longer escape routes in a tunnel. Such an incident is very difficult to control, and so a certain element of risks remains, despite the best and most careful planning.

If an air flow is prevented because the air cannot escape, this is referred to as an accumulation of compressed air. In Lot C of the new City Tunnel in Leipzig, a connection to Leipzig main station was required. By analogy with the construction measures in Lot B of the City Tunnel, this was to be effected using mining methods with two conventional tunnel drives with additional ice formation here under the protection of pile planking and sealing bases directly under the foundation of the existing main station (Figure 7). An air flow was not possible here because of the upwards seal of the connection point by the impermeable base plates of the station, the lateral seal with airtight walls, and downwards thanks to the integration in dense soil layers or integrated sealing bases, so that this construction method could not be used here.

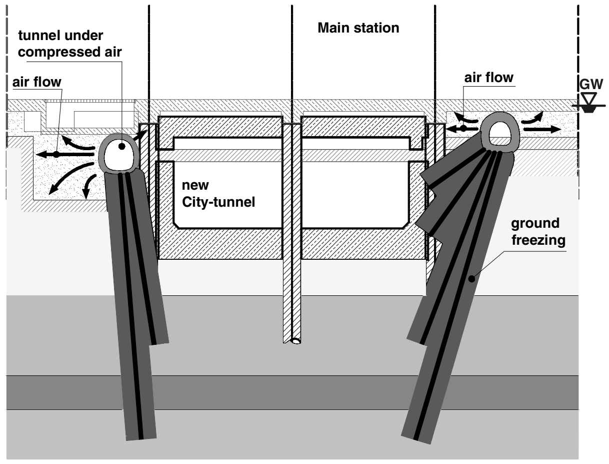

Figure 7. Tunneling under Leipzig main station

REFERENCES

Becker, H. & Baumann, Th. 1986. *Wasserhaltung durch Druckluft bei Spritzbetonbauweisen.* In. Bauingenieur 61, pp. 389-397

Elsner, P., Mörchen, N., Babendererde, T., Kirsch, F. & Schmidt, J. 2008. *Räumung der Tunneltrasse mit Vereisungs- stollen und Druckluftvortrieben unter der Innenstadt von Leipzig.* In: Baugrundtagung 2008 Dortmund, pp. 239 -245

Fuchsberger, M., Strobl, B., Ayaydin, N. & Heinrich, R. 1988. Tunneling under compressed air in granular soils –research, design an site experience. In: Proceedings of the International Conference on Tunnels and Water

Gülzow, H.-G. & Wittke, W. 1996. *Dreidimensionale Berechnung der Zweiphasenströmung beim Tunnelvortrieb unter Druckluft.* In: Taschenbuch für den Tunnelbau, Verlag Glückauf, pp. 21-65

Kramer, J. & Semprich, S. 1989. *Erfahrungen über Druckluftverbrauch bei der Spritzbetonbauweise.* In: Taschenb.für den Tunnelbau, Verlag Glückauf, pp. 91-153

Rieker, K. 1992. *Spritzbetonbauweise unter Druckluft.* Dissertation, University of Insbruck, Austria

Schmidt, H. G. & Seitz, J. 1998. *Grundbau.* In: Betonkalender, Verlag Ernst & Sohn, Berlin

Wagner, H. 1968. *Der Druckluft-Schildvortrieb.* Verkehrs-Tunnelbau, Band I, Verlag Wilhlem Ernst & Sohn, Berlin - München