Tunnelling and Underground Space Technology 25 (2010) 114–121

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Drip sealing of tunnels in hard rock: A new concept for the design and evaluation of permeation grouting

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ARTICLE INFO

Article history:
Received 14 January 2009
Received in revised form 2 September 2009
Accepted 29 September 2009
Available online 24 October 2009

Keywords:
Grouting design
Grouting evaluation
Dripping
Hard rock
Cement
Silica sol

ABSTRACT

This paper presents a new pre-excavation grouting concept to prevent dripping and reduce the inflow into a railway tunnel. For this purpose, the tunnel's roof was drip-sealed using colloidal silica and the walls and invert of the tunnel were grouted with cement. The grouting design process followed a structured approach with pre-investigations of core-drilled boreholes providing parameters for the layout. Water pressure tests and pressure volume time recordings were used for the evaluation. Results showed that the design was successful: the total transmissivity was reduced from 4.9×10^{-08} m^2/s to the measurement limit (1.6×10^{-08} m^2/s), and the dripping was reduced to eight spots from the roof. Improved rock characterisation showed that the grout hole separation was within the transmissivity correlation length and that grouting efficiency depends to a large extent on the dimensionality of the flow system of the rock mass.

1. Introduction

Groundwater inflow is a common problem in hard rock tunnels during and after construction. Major inflows will delay or stop tunnel construction, damage the tunnel structure and, if the water table is lowered sufficiently, damage the surrounding environment. Minor inflows such as dripping are not usually a problem although they could damage the installations and equipment inside and in cold conditions it will lead to the build-up of icicles on the roof and walls and degradation of the structure due to frost heave increasing the cost of maintenance. Consequently, groundwater control is essential to reduce costs and this can be achieved by grouting.

Permeation grouting in hard rock tunnels involves filling fractures with grout in order to reduce the permeability of the rock. In practice, to achieve the intended purpose boreholes are drilled into the rock mass and grout is injected under pressure until the fractures around the borehole are filled (Nonveiller, 1989). The complete filling of these fractures may be possible if they are connected to each other in such a way that the remaining water and air can be displaced outside the designed grouting zone (Kutzner, 1996). Fractures vary in size, volume, and configuration making it difficult to know if they are connected and whether or not they were completely filled with grout. The reason for and the extent of these variations are influenced by the origin, age and stress history of the rock being studied (Warner, 2004).

Fracture variation is not the only concern in grouting. In permeation grouting, fine-grained cementitious grouts have been widely used around the world for the last decade (Stuart, 2003). Most cementitious grouts used can penetrate fractures with a hydraulic aperture down to 100 μm although the requirement of complete waterproofing, e.g. no dripping from the roof of a tunnel, requires new permeation grouts that help to satisfy the demands. Non-cementitious grouts may do the job since these can penetrate fractures with smaller hydraulic apertures.

Colloidal silica has been studied and used in some underground constructions. Funehag (2007) investigated the sealing efficiency and penetrability of colloidal silica in the partly excavated tunnel in Hallandsås in southern Sweden. Results showed that colloidal silica penetrates narrow fractures and that the hydraulic conductivity of the rock mass can be reduced to 10^{-9} m/s. Field tests conducted by Funehag and Gustafson (2008) in the Törnskog Tunnel in the east of Sweden focused on the practical aspects of the grouting procedure. Results showed that a grouting design can be put into practice, reducing the water ingress into a tunnel to a required level.

However, to our knowledge these studies have not examined the possibility of combining both grout types to achieve the combined aims: to prevent dripping from the tunnel roof and to reduce the inflow from the tunnel walls and invert down to the permitted level. Hence, the aims of this paper are to introduce a new pre-excavation grouting concept and design to prevent dripping, and reduce the inflow to satisfy an overall maximum level.

The field test was conducted in the Nygård Tunnel, which is located in western Sweden. A total of 86 m of the main tunnel, which

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doi:10.1016/j.tust.2009.09.008

is approximately 3 km long, followed the suggested pre-excavation grouting design. The design was used in five grouting fans of 23.6 m each with 8 m of overlap between the fans. The main tunnel is 10 m high and 13 m wide and is located 40–50 m below the ground surface. The rock type in the excavation area is mainly gneiss with a small fraction of amphibolites.

2. Drip sealing and inflow reduction concept

Fig. 1 illustrates the approach. The tunnel's roof is drip-sealed using silica sol and the walls and invert of the tunnel are grouted with cement. Also shown are the alternative paths for water to ingress into the tunnel due to the difference in gradient created by the grouted section transmissivities.

3. Materials and methods

3.1. Grouting design process

Whether the aim is to waterproof or to reduce the inflow, a planned strategy is required. Gustafson et al. (2004) illustrated the steps for a structured grouting design and analysis, which was also followed in this study, see Fig. 2.

3.1.1. Pre-investigations

During the pre-investigations pressure build-up tests (PBTs) were conducted in four core-drilled boreholes and the specific capacity at 3 m intervals was evaluated. A complete fracture distribution analysis was also made using all four boreholes combined, Fransson (2001a). In Fig. 3 the fracture frequency and the calculated transmissivities of the tested intervals are presented.

3.1.2. Fracture transmissivity and aperture distributions

Using the fracture distribution and the calculated transmissivities a Pareto or power-law distribution, based on the maximum fracture transmissivity value ($T_{\max}$) and the probability that a transmissivity is below a certain transmissivity (T_r), was obtained (Gustafson and Fransson, 2005). The Pareto distribution is then approximated as a straight line in a log–log plot, see Fig. 4. This line has a slope $-k$ (coefficient of the distribution) which was used to evaluate the hydraulic aperture distribution.

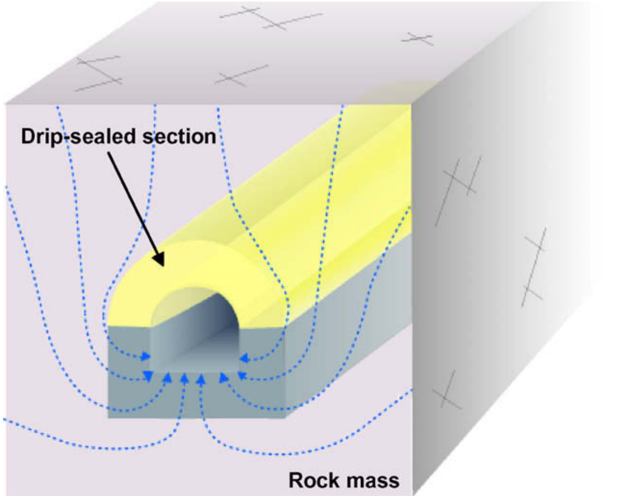

Fig. 1. Illustration of the dripping separation concept in the Nygård Tunnel. The coloured areas are the theoretical grouted regions for each grout. The broken lines show the alternative paths for the water to ingress into the tunnel. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

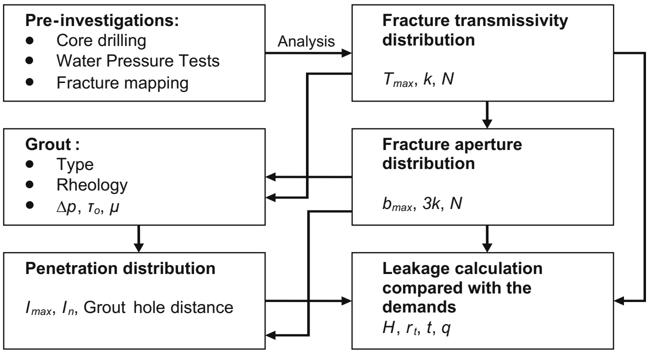

Fig. 2. Illustration of the grouting design process approach.

Using the cubic law, Eq. (1), the hydraulic aperture can be evaluated (Fransson, 2001b):

$$b = \sqrt[3]{T \cdot \frac{12 \cdot \mu_w}{\rho_w \cdot g}} \tag{1}$$

By ranking the hydraulic aperture and using the coefficient $(-k)$ from the calculated Pareto distribution, the hydraulic aperture of the fracture, rank r, will be:

$$b_r = b_{\max}/r^{1/3\cdot k} \tag{2}$$

The last equation uses $b_{\max}$, which was the largest hydraulic aperture that corresponded to the highest transmissivity previously observed. Using Eq. (2) and the Pareto distribution coefficient, the hydraulic aperture distribution was estimated, see Fig. 5. As can be seen, around 97% of the fractures have a hydraulic aperture of less than 0.1 mm and around 60% of them have an aperture of less than 0.014 mm.

3.1.3. Grouting agents

Cementitious and non-cementitious grouts are the two main groups of grouting agents and the selection depends a great deal on the aims of the project. The grouts used here were: Injektering 30 (IC 30), a Portland cement grout that is sulphate-resistant with a low alkalinity and in which 95% of the particle sizes are smaller than 30 μm (Cementa, 2007). IC 30 was mixed with regular water and a superplasticiser 'SetControl II', to regulate the setting time and disperse the suspension. Cementitious grouts are generally characterised as Bingham fluids.

Cementitious grouts can penetrate and seal fractures that are about three times their particle size (Mitchell, 1981). IC 30 can thus penetrate fracture apertures bigger than approximately 0.1 mm. Silica sol on the other hand can penetrate and seal smaller fractures, which may cause a dripping problem in tunnels.

Meyco MP320T is a colloidal silica grout. It is odourless, salty, and non-toxic. Colloidal silica consists of nanometre-sized particles of amorphous SiO_2 cores with hydroxylated surfaces. The particle sizes in the material can vary from 1 to 500 nm (Björnström, 2005). Meyco MP320T is manufactured by Eka Chemical AB and was mixed with a salt solution (NaCl) in order to initiate particle aggregation, which hardens the sol to a gel. It is characterised as a Newtonian fluid before gelling (Funehag, 2007).

Once the grouts were chosen, their rheology was investigated. The initial yield stress (τ_o) and initial viscosity (μ) and other features were determined by means of laboratory tests for the two grout types, see Table 1.

3.1.4. Penetration distribution

The penetration of the grout into the fractures to be sealed depends on the type of grout used. For a cement grout its penetration