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Re-injection of groundwater by pressurizing a segmental tunnel lining with permeable backfill

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ABSTRACT

Recently, within a tunneling project, a method for reinjecting discharged groundwater at tunnel level has been investigated. The method was performed by pressurizing a long section of the lining with un-grouted pea gravel as backfill, in a rock mass with low hydraulic conductivity. Water was reinjected through watertight lining into a section where un-grouted pea gravel was used as backfill. The pressure response was measured both behind the lining and in the rock mass, the latter by means of several observation wells drilled from ground level. Reinjecting water into a rock mass by pressurizing a lining with a permeable backfill (such as un-grouted pea gravel) was found to be possible and feasible. Well testing methods developed for vertically drilled wells, such as a step injection test and constant head/pressure tests, were used and found to be applicable, even for testing at tunnel level. It was also found that well known analytical solutions, developed for vertically drilled wells, can be used for interpretation, e.g. transmissivity from tests performed at tunnel level and from the pressure response in two of the observation wells.

1. Introduction

Most underground projects must conform to restrictions concerning the amount of permitted groundwater discharge arising from the project. This is the case at the Hallandsås tunnel project in Sweden, where the water permit is set at a 30 day rolling average of 100 l/s. This permit is based on an assumption of the environmental impact caused by temporary groundwater drawdown. In this case, the water permit governs the tunneling project and different treatments are carried out at the Tunnel Boring Machine (TBM), in order to control the amount of water discharge from the project. TBM lining with grouted backfill is an initial design to avoid an overly large influx of groundwater. Recently, within the project, a method to reinject the discharged groundwater has been investigated. This was done in order to reduce the importance of the strict permit limit of 100 l/s, thereby increasing the rate of tunneling progress. The method was performed by pressurizing a long section of the lining with un-grouted pea gravel as backfill, in a rock mass with low hydraulic conductivity. The water was reinjected through the watertight lining into a section where un-grouted pea gravel was used as backfill. The pressure response was measured, both in the backfill and in several observation wells in the surrounding rock mass. The observation wells are drilled from ground level. Un-grouted pea gravel was used as back fill material only during the production of the tunnel; the section has now been grouted.

The main goal of this feasibility study was to evaluate the applicability of the method for re-injection of discharged groundwater. In addition, the applicability of well testing methods adopted from the groundwater industry, such as the constant head test and the step injection test were evaluated for a tunnel environment. A different approach is also used for the evaluation of the testing, where well known interpretation methods for displacement and time data are used for the interpretation of transmissivity. Methods like Cooper and Jacob (1946) and Jacob and Lohman (1952) are applied, these methods having been developed for vertical wells. Another approach used was to consider the tunnel as a horizontal well and use a solution developed by Daviau et al. (1988) for the interpretation of transmissivity. Transmissivity is estimated by using data obtained from pressure sensors in the tunnel and measuring the pressure outside of the lining, as well as using data acquired from observation wells.

The method for re-injection of water through the lining was tested during a TBM maintenance stoppage. Consequently, the method's applicability during TBM operational conditions still remains an issue. However, the pump installation did not interrupt logistical operations in the tunnel. Another remaining issue is how to collect and treat water for re-injection. For permanent re-injection, water from the tunnel process needs proper treatment

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before being injected. During the injection tests, clean water from a reservoir located outside the tunnel was used.

1.1. Hallandsås project and geology

The Hallandsås project is an ongoing project consisting of two 8.6 km long single track railway tunnels through the Hallandsås Horst in southern Sweden. The tunnels are constructed using a Tunnel Boring Machine (TBM). The TBM has a diameter of 10.6 m and the tunnels are lined with segmental lining. The lining has an outer diameter of 10.12 m, creating an annulus of 24 cm between the rock tunnel and the lining. This annulus volume is filled with backfill material. During the first stage of production the backfill consists of mortar and un-grouted pea gravel. The pea gravel is grouted at a later stage. A detailed description of the project can be found at e.g. (Banverket, 2009). The Hallandsås horst is a part of the Tornquist zone, which is one of the major geological structures in northern Europe. The zone has a north-west to south-east orientation and stretches from the North Sea to the Black Sea. The dominating fracture and fault systems in the horst are aligned in this direction. The tunnels are built sub-perpendicular to these structures. Another strongly developed fracture system is located in a north–northeast to south–southwest direction (Wikman and Bergström, 1987). However, the Horst has a long and complex geological history and many different fracture systems are present. The fractured basement of the horst is an important groundwater resource with substantial quantities of water. Gneiss is the dominating rock type (80%), followed by amphibolite (15%), with smaller quantities of dolerite and granite also present. The horst is built up of several tectonic blocks separated by fault zones within the major Tornquist zone, so there is a great variation in rock quality. As the tunneling propagates from one tectonic block to another, separated by a tectonic zone, the rock mass quality varies from unweathered to completely weathered and from solid to highly fractured.

1.2. The selected test section

The selected test section for re-injection of groundwater was situated between concrete Rings #818 and #972 (see Fig. 1). The total length of the section is around 350 m and the backfill consisted of un-grouted pea gravel only. The section is confined to the north-east and southwest by tunnel sections with mortar as backfill. The test section is located between two major dolerite dikes. These dikes limit the aquifer unit affected by this test (see Fig. 1). The dolerite dikes in Hallandsås constitute an almost watertight rock unit with slightly increased permeability in the upper part. During the test, the TBM was standing at the mid-adit (Ring #1160) north-east of the dolerite dike shown in Fig. 1. Hence, drainage around the TBM was mainly affecting the aquifer unit north-east of the test section and the pressure recorded in this unit was 10 bar. The measured groundwater pressure at tunnel level in the test section was 13.1 bar, and the aquifer was still slowly recovering from the drainage caused by the tunneling. The pressure will increase to approximately 14 bar when the aquifer unit is fully recovered.

The test section from Ring #818 to Ring #972 was relatively dry during TBM excavation and the dominating rock type is gneiss. Typically the rock mass was unweathered and had a block size of 20–60 cm (RQD: 50–75), corresponding to Hallandsås rock class 2. Pea gravel consisting of an equal mixture of 3–10 mm and 8–16 mm was used as backfill. The pea gravel is of glacial fluvial origin and the well rounded gravel had been sieved and washed. The dominating rock type in the gravel was high strength gneiss.

The observation wells used during the testing can be seen in Fig. 1 and also on the map in Fig. 2. The wells were drilled down to the tunnel level and are used for observations of the groundwater levels within the Hallandsås project's ecological control program.

1.3. Test setup

For this test, water from the clean water pond and a well outside the tunnel was used, with both sources analyzed and found to be comparable with the natural ground water at Hallandsås. The clean water was fed into a tank inside the tunnel and connected to the injection pump (see Fig. 3). The pump was connected to the tank at the intake side and, through a bypass system, to the discharge side (see Fig. 3). A valve attached to the bypass system was used for regulating injection pressure during testing. The manifold was equipped with check valves in order to prevent groundwater flowing backwards into the pump and the bypass system. As an extra mitigatory measure, pressure relief valves were mounted on the manifold. Pressure sensors and flow meters were attached along the manifold (see Fig. 3). The manifold was connected to eight injection hoses, which were connected to injection sockets in the lining, thus establishing communication with the formation. The injection points were equally spaced in pairs over a distance of around 30 m (one on each side of the tunnel ring).

Main components in the test setup were:

- Multistage pump 135 kW, 50 l/s at 20 bar (MULTITEC, MTC A 100/03-08.1).
- 5 m^3 water tank.
- Eight injection hoses (1.5 in.) with injection sockets and valves.
- Steel manifold (4 in.).
- Bypass system including high precision regulation valve.
- Flow meters and pressure sensors.
- Pressure relief valves, 15 and 18 bar.
- Check valves, preventing pea gravel and water from outside the lining entering the system.
- Pipes from clean water line to tank, with regulation valve.

In order to monitor this test flow meters and pressure sensors were installed on the manifold. In addition, six pressure sensors were installed along the lining, measuring the pressure distribution behind the lining (see Fig. 4). Pressure sensors were placed both inside and outside of the test section (see Fig. 4). Pressure data was also acquired during testing from observation wells in the vicinity (see Fig. 2). All the collected data was automatically logged. However, manual readings were carried out continuously as a back up during the tests.

From a mechanical point of view, the lining is sensitive to an asymmetric load so, for safety reasons, as well as to gain experience in the matter, the segmented lining was carefully monitored during testing. Monitoring was carried out using a combination of inclinometers and traditional convergence measurements. The traditional convergence measurement gives the horizontal diameter. Inclinometer measurements reveal both the shape of the ring (ovalisation) and the convergence of the ring (diameter). The inclinometer measurements were performed continuously and the convergence measurements after every injection pressure increase.

2. Results and interpretation

Three injection tests were carried out to evaluate the possibility of reinjecting water by pressurizing a tunnel section with un-grouted pea gravel backfill. The first test was conducted in order to check the test setup. The second test performed was a step injection test and the third a constant pressure test.

2.1. Step injection test results

The step injection test was performed in three different steps using pressure increases of approximately 0.5 bar, 0.8 bar and