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Impact of tunneling on regional groundwater flow and implications for swelling of clay–sulfate rocks

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ABSTRACT

Tunnels play a key role in many transportation concepts. The swelling of clay–sulfate rocks leads to serious damage to many tunnels crossing such rock, producing great difficulties and high extra costs in tunnel engineering. The swelling is caused by the transformation of the sulfate mineral anhydrite into gypsum, entailing a 60% volume increase. The transformation involves anhydrite dissolution in water, transport of the solution with groundwater flow, and gypsum precipitation at a different location. Therefore, the knowledge of groundwater flow systems at the tunnel and adjacent areas is essential to better understand the swelling processes. The present study investigates the groundwater flow systems at the Chienberg tunnel in Switzerland before and after the tunnel excavation, based on numerical flow modeling. The models include faults and the hydrostratigraphic layering in the subsurface to assess the role of the hydrogeological setting. The results of this study indicate effects on groundwater flow caused by the tunneling, which may trigger rock swelling by favoring anhydrite dissolution and gypsum precipitation, including (1) increase of flow rates around the tunnel, (2) broadened, shifted and more distributed capture zones leading to a change in origin and age of groundwater, (3) access of groundwater from preferential flow paths (e.g. faults) due to the drainage effect of the tunnel, and (4) change in geochemical equilibrium conditions because of decreased pore water pressures in the tunnel area.

1. Introduction

Efficient transport strongly relies on road and railway tunnels, both in long-distance traffic (e.g., European alpine transit) and in metropolitan areas. The swelling of clay–sulfate rocks poses a severe threat to this important infrastructure. The problems associated with swelling clay–sulfate rocks are well known in tunnel engineering (Einstein, 1996): The swelling may result in a heave of the tunnel floor, destruction of the lining or uplift of the entire tunnel section, producing major difficulties and high additional costs during tunnel construction and maintenance. Worldwide, extensive repair work in tunnels due to the swelling of clay–sulfate rocks was, and still is, necessary. European examples include several tunnels in the Jura Mountains in Switzerland (e.g., Belchen, Chienberg, Adler tunnel), and tunnels around the Stuttgart metropolitan area in southern Germany (e.g., Wagenburg, Engelberg, Freudenstein tunnel). In these examples, the difficulties are associated mainly with the Triassic Gipskeuper ("Gypsum Keuper") Formation.

The threats imposed by swelling clay–sulfate rocks in tunneling are mostly counteracted on an engineering level by constructive measures. Measures include either the application of a strong, rigid supporting formwork to limit deformation, or allowing floor heave in an excavated zone under the tunnel floor to limit swelling pressures (Pierau and Kiehl, 1996). Other authors suggest combining both strategies by implementing a deformable zone (Kovári and Chiaverio, 2007). However, there is no consensus among experts as to which measure is most appropriate. The reason for this lack of consensus is the limited understanding of the involved processes during swelling in such rock (Anagnostou, 2007). To date, there is no accepted relation describing the swelling heave as a function of swelling pressure in clay–sulfate rocks. Field and laboratory measurements often give contradictory indications of the magnitude of swelling heaves and pressures (Madsen and Nüesch, 1991; Nüesch et al., 1995; Pimentel, 2007), and the results from one site cannot directly be transferred to other sites. For these reasons, reliable predictions of expected swelling heaves and pressures at an actual construction project are not yet possible.

Generally, the swelling is caused by the transformation of anhydrite into gypsum under water uptake (hydration of anhydrite). Gypsum is subject to a 60% increase in volume, compared to anhydrite. An important reason for the uncertainties described above is the fact that the transformation of anhydrite into gypsum does not take place directly, but indirectly via anhydrite solution, followed by gypsum precipitation (Jeschke et al., 2001). Between dissolution and re-precipitation, the solutes are transported with groundwater flow, i.e., dissolution and precipitation occurs at different locations.

Rock swelling does not occur every time a tunnel is constructed in clay–sulfate rocks. An explanation for this is provided by the

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fundamental work of Tóth (1999). He demonstrated that geochemical conditions in the subsurface, such as redox potential, pH and ion concentrations, depend on groundwater residence times and flow patterns or, generally, on the hydrogeological setting. The regional groundwater flow system is therefore a key factor controlling dissolution and precipitation of the sulfate minerals in clay–sulfate rocks, and the knowledge of hydraulic head field at a regional scale is a major requirement for understanding the swelling phenomena. In spite of the important role of the groundwater system in understanding the swelling processes in clay–sulfate rocks, the relation between hydrogeological setting and swelling has not been investigated so far.

Because swelling often starts immediately after tunnel excavation, fast changes in the groundwater flow system are likely to be responsible for the observed swelling phenomena. The generation of fractures in the excavation damaged zone (Tsang et al., 2005) around the tunnel, which is induced by the tunnel excavation and resulting stress redistribution, involves a sudden increase of rock permeability. In addition, atmospheric pressures exist at the tunnel walls after tunnel excavation, leading to a decrease in pore water pressure around the tunnel. The effect of these changes induced by the tunnel excavation on the regional flow field is an important issue to be evaluated in detail, because changes in regional groundwater flow may significantly change the geochemistry of the pore water. For example, these changes my produce rapid access of meteoric surface water or formation water with relatively low ion concentrations to the clay–sulfate rocks.

This study investigates the effects of a tunnel excavation on regional groundwater flow systems depending on the hydrogeological setting. The aim is to provide a conceptual framework to define the relations between morphological, hydrological and geological structures and rock swelling. These relations are a first step towards understanding the complex coupled hydraulic-mechanical and geochemical processes that occur during rock swelling. The overall aim is to contribute to an improved scientific basis for decisions made during project planning, cost planning and realization of tunnel projects in clay–sulfate rocks.

2. Methodology

2.1. Test site

The test site of the present study is the Chienberg road tunnel, which was built between 2000 and 2006 to bypass the town of Sissach in Switzerland (Figure 1). Already during construction of the tunnel, major problems occurred with the swelling of clay–sulfate rocks of the Gipskeuper ("Gypsum Keuper") Formation. During a lengthy interruption of the excavation, the open floor of the tunnel experienced a heave of about 1.5 m within three months at the top heading. The swelling continued after the installation of the supporting formwork and lead also to heaves of the ground surface above the tunnel, hence, causing damage to houses. Observable swelling phenomena are restricted to two separate sections of the tunnel. Other sections that also cut the Gipskeuper Formation are, until date, not subject to swelling. Expensive countermeasures, including the construction of a deformable zone under the road surface, have been successfully implemented to prevent further heave of the road surface in the tunnel and the ground surface above (Kovári and Chiaverio, 2007). The swelling process in the deformable zone, however, continues to date.

The study area is part of the Swiss Jura Mountains. The Jura Mountains are subdivided into the Tabular Jura in the North, and the Folded Jura in the South (c.f. Figure 1). The Folded Jura is thrusted northward over the Tabular Jura. The Chienberg tunnel is located in the Tabular Jura near to the main thrust of the Folded Jura. The geological units of the Jura Mountains comprise Triassic and Jurassic sediments of varying hydraulic permeability overlying a pre-Mesozoic basement (Figures 2 top and 3). The units of the Tabular Jura are nearly flat lying and have experienced an extensional deformation, resulting in mainly SSW–NNE oriented horst and graben structures. The units of the Folded Jura were deformed under compressional conditions, resulting in W–E oriented folds and thrusts.

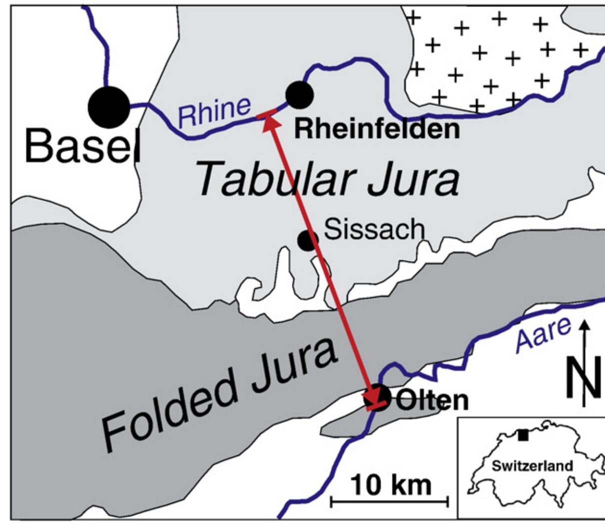

Fig. 1. Study area and location of the cross-section of Fig. 2 (arrow).

The tunnel crosses Quaternary sediments near the surface, and Mesozoic bedrock with a stratigraphic extent reaching from the Gipskeuper Formation (bottom) to the Opalinus Clay Formation (top). The Quarternary sediments consist of fluvio-glacial gravels close to the valley of the nearby river Ergolz, and colluvium at the slopes of the hill Chienberg. The Mesozoic bedrock is dominated by argillaceous marlstone with some dolomitic interbeds. Large parts of the tunnel cross the Gipskeuper Formation, containing the sulfate minerals anhydrite and gypsum. These minerals appear as thin layers, nodules and veins, as well as finely dispersed in a clay–marlstone rock matrix. Close to the surface, the sulfate minerals are often leached.

2.2. Model concept

The hierarchical nature of the topography leads to a hierarchical pattern of flow systems: Generally, regional, intermediate and local flow systems can be distinguished. Groundwater flow at a certain location can be described as a superposition of these topographically driven systems (Zijl, 1999). To understand the effects of a tunnel excavation on local groundwater flow at the tunnel scale, it is important to include also the intermediate and regional flow systems. For this reason, the investigations of the present study are conducted at a regional scale.

Another advantage of considering groundwater flow at a regional scale concerns the boundary conditions. Typically, there are no or very little measurements of the hydraulic head in the bedrock to define boundary conditions. At a regional scale, however, realistic assumptions of boundary conditions can be made:

1. Major receiving streams drain regional groundwater flow systems and therefore mark regional groundwater divides (Freeze and Witherspoon, 1967). It is therefore reasonable to assume no flow conditions perpendicular to a vertical line through stream valleys.
2. The water table can be approximated by the topographic level of the ground surface at a regional scale (Hubbert, 1940; Tóth, 1963), allowing to assign a constant head boundary to the ground surface with the hydraulic head corresponding to the elevation.