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Swelling potential of clay-sulfate rocks in tunneling in complex geological settings and impact of hydraulic measures assessed by 3D groundwater modeling

Christoph Butscher [a,*], Stefan Scheidler [b], Hadi Farhadian [c], Horst Dresmann [b], Peter Huggenberger [b]

[a] Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Division of Engineering Geology, Kaiserstr. 12, 76131 Karlsruhe, Germany
[b] University of Basel, Institute of Geology and Paleontology, Applied and Environmental Geology, Bernoullistrasse 32, 4056 Basel, Switzerland
[c] Amirkabir University of Technology (Tehran Polytechnic), Department of Mining and Metallurgical Engineering, Hafez Ave., P.O. Box 44113-15875, Tehran, Iran

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ABSTRACT

Swelling of clay-sulfate rocks is a feared problem in tunneling in such rock, causing heave of the tunnel invert and leading to swelling pressures that seriously damage the tunnel lining. Prediction of the swelling potential of rocks in different tunnel sections and tools to evaluate measures that aim at reducing the swelling risk would be a major aid for designers of tunneling projects and rehabilitation works in order to respond adequately to the swelling problem. The study presents a hydrogeological approach to assess the swelling potential of clay-sulfate rocks in tunneling, using the Belchen tunnel in Switzerland as a case study. It shows that this approach can be applied to complex geological settings using structurally consistent 3D numerical models to simulate groundwater flow influenced by tunneling. The models are in particular used to evaluate hydraulic measures that aim at preventing or minimizing water inflow into clay-sulfate rocks after tunneling. Analyzed hydraulic measures include pumping shafts connected to the tunnel drainage, sealing structures applied to the rock zone around the tunnel damaged by the excavation process (excavation damaged zone), as well as groundwater level drawdown in aquifers crossing the tunnel. A sensitivity study addresses model uncertainties and evaluates the impact of model parameters on the swelling potential. Promising measures include the installation of pumping shafts in tunnel sections of clay-sulfate rocks at the border to aquifers and permeable fault zones. The study shows that monitoring of hydraulic heads as well as of groundwater volumes drained by the tunnel would increase the predictive capability of the models. Presented results are site specific. However, the approach to assess the swelling potential of clay-sulfate rocks in tunneling, and to assess hydraulic measures to respond to the swelling problem, can be transferred to other tunneling projects.

1. Introduction

Tunneling in clay-sulfate rocks often leads to swelling problems, which are manifested in heave of the tunnel invert or sometimes even entire tunnel sections and the ground surface above the tunnel; and restrained swelling heave leads to the development of swelling pressure that damages the tunnel lining (e.g., Anagnostou et al., 2010; Einstein, 1996; Steiner, 1993). The "swelling problem" is a formidable phenomenon especially in the Swiss Jura Mountains and the Stuttgart metropolitan area in Germany (e.g., Berdugo et al., 2009a, 2009b), where tunnels often need to cross clay-sulfate rocks of the Triassic Gipskeuper ("Gypsum Keuper") formation. However, swelling phenomena and associated engineering problems are reported world-wide, for example from Tertiary clay-sulfate rocks in Spain (Alonso et al., 2013) and from other countries, including France, Saudi Arabia, Poland, Italy and Texas/USA (Yilmaz, 2001, and references therein). More recently, the swelling problem was also encountered after the drilling of boreholes for geothermal installations. Examples include the historic town of Staufen and other settlements in Southern Germany (Grimm et al., 2014; Ruch and Wirsing, 2013; Sass and Burbaum, 2010). The drilling of boreholes led to changes in flow regime and subsequent groundwater inflow into clay-sulfate rocks of the Gipskeuper formation. As a result, swelling occurred that led to heave of the ground surface and dramatic damage to houses.

The basic processes leading to swelling of clay-sulfate rocks include both "sulfate swelling" and "clay swelling" (e.g., Madsen and Nüesch, 1991). Sulfate swelling is caused by the hydration of the sulfate mineral anhydrite, which is transformed into gypsum ($CaSO_4 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O$; e.g. MacDonald, 1953). The mole volume of gypsum is

* Corresponding author.
E-mail address: christoph.butscher@kit.edu (C. Butscher).

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61% greater than the mole volume of anhydrite. Clay swelling is caused by osmotic water inflow between clay particles (Madsen and Müller-Vonmoos, 1989) and also by the hydration of certain clay minerals (Kraehenbuehl et al., 1987). Swelling heaves and pressures observed in clay rocks without sulfates are much lower than swelling heaves and pressures typically observed in clay rocks containing sulfates (e.g., Flückiger et al., 1994; Madsen et al., 1995; Steiner, 1993). Therefore, sulfate swelling is considered as the main mechanism contributing to the swelling of clay-sulfate rocks (e.g., Serafeimidis and Anagnostou, 2014; Wittke et al., 2004). However, the exact role of clay swelling in the swelling of clay-sulfate rocks is not yet fully understood (Anagnostou et al., 2010; Butscher et al., 2016).

Constructional measures to respond to the swelling problems either aim at opposing swelling heave by implementing a mechanical resistance (rock anchors, reinforced lining, etc.); at reducing swelling pressure by allowing deformation; or at a combination of both strategies (Kovári and Chiaverio, 2007; Pierau and Kiehl, 1995). In practice, finding the most appropriate tunnel design is hampered by the problem that there is no generally accepted swelling law that would allow engineers to predict swelling heave or pressure (Anagnostou et al., 2010; Butscher et al., 2017).

Hydraulic measures may be a further approach and a practical way to respond to the swelling problem. As outlined in the beginning of this chapter, the different swelling mechanisms all require the presence of water. Therefore, it is self-evident that groundwater flow is an important controlling factor for swelling, albeit groundwater flow rates in clay-sulfate rocks are small and may not be recognized during tunnel construction. The relation between groundwater flow and swelling phenomena in tunnels in clay-sulfate rocks was investigated by Butscher et al. (2011a, 2011b, 2011c) and Huggenberger and Butscher (2012). They showed that swelling is triggered by changes in groundwater flow systems after tunneling, and pointed at hydrogeological conditions that favor swelling. In another study, Butscher et al. (2015) presented an approach to assess the swelling potential of clay-sulfate rocks in tunneling using Darcy flux as a hydrological indicator. They also derived hydraulic parameters that have strongest impact on the swelling potential. Based on this study, they discussed implications for site investigation and for measures to counteract the swelling problem.

The above mentioned research investigated hydrogeological conditions using two-dimensional (2D) groundwater models. The present study, however, requires a three dimensional (3D) approach, because the geological setting is rather complex with thrust related folding (Suppe, 1983) and both thrust and transform faulting. The geological complexity causes also the assessment of the hydrogeological flow regime to be a complex 3D problem. Therefore, the first and original aim of the present study is to show how the previously established 2D approach can be transferred to complex geological settings using true 3D model geometries. The second aim of the study is to use the developed models for an evaluation of possible hydraulic measures and their impact on the swelling potential of tunnel sections built in clay-sulfate rocks, using the Belchen tunnel as a case study. In addition to the general design of the tunnel drainage, the analyzed hydraulic measures include pumping shafts connected to the tunnel drainage, sealing structures located in the excavation damaged zone (EDZ) surrounding the tunnel, and groundwater level drawdown in aquifers crossed by the tunnel. The study describes the set-up of 3D numerical groundwater models and presents the simulated groundwater circulation at the study site before and after tunneling. Hydraulic measures are analyzed in scenario simulations and evaluated with respect to the swelling potential of tunnel sections built in the Gipskeuper formation. A sensitivity study addresses model uncertainties and evaluates the impact of model parameters on the swelling potential. The article discusses the study's implications and closes with conclusions for tunneling in clay-sulfate rocks.

2. Study site

The study was carried out for the Belchen tunnel in Northwest Switzerland, located between the cities Basel and Olten (Fig. 1a). It is part of the national highway N2 and was built between 1963 and 1970. The 3.18 km long road tunnel consists of two separate two-lane tubes, connected by seven drifts, and three vertical ventilation shafts. The maximum overburden thickness is about 370 m. Tunnel advance was realized by blasting. Construction started with the excavation of two sidewall drifts, where the foundation of the top heading was concreted, followed by an enlargement to the final profile. Already during construction, more than 1 m heave of the tunnel invert and damage to the (non-reinforced) 0.45 m thick invert arc were observed in sections crossing clay-sulfate rocks of the Triassic Gipskeuper formation (Amstad and Kovári, 2001). A reinforced, 0.85 m thick invert arc was then built as response to the swelling. Fig. 1b shows a cross-section of the tunnel profile, illustrating the original and the renewed invert arc and drainage system. Since the opening of the tunnel in 1970 though, damages to the tunnel lining due to swelling continued, making repeated rehabilitation work necessary. In 1999, a 360 m long experimental drainage adit (c.f., Fig. 2) combined with drainage boreholes was built under the two tubes of the tunnel in a section located in the Gipskeuper formation, with the aim of dewatering the swelling rock (Amstad and Kovári, 2001; Anagnostou et al., 2010). This measure, however, did not show any success in terms of reducing swelling pressures or deformation. Currently, the excavation of a third tube just began to allow

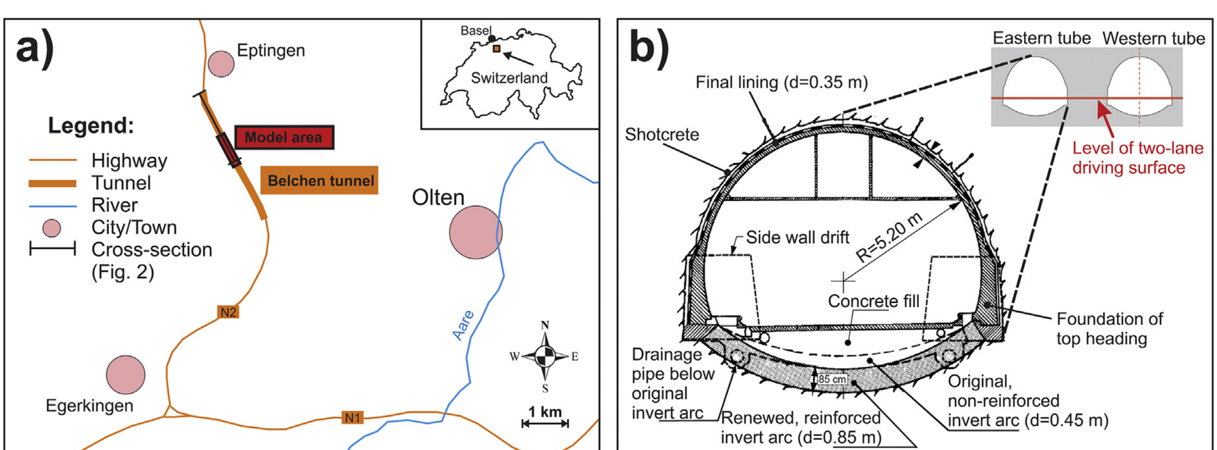

Fig. 1. Location of study site and model area (a) and illustration of the tunnel design (b) (after Amstad and Kovári, 2001).