Swelling of clay-sulfate rocks: A review of processes and controls

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Abstract
The swelling of clay-sulfate rocks is a major threat in tunnel engineering, causing serious damage to tunnels and producing high additional costs during tunnel construction and operation. The swelling problem is also known from other geotechnical fields, such as road and bridge construction, and in conjunction with geothermal drillings. The planning of counter measures that would stop or minimize the swelling is extremely difficult, and it is currently impossible to predict the swelling behavior of an actual geotechnical project. One of the reasons is our limited knowledge of the processes involved in the swelling of clay-sulfate rocks, and of the geological, mineralogical, chemical, hydraulic and mechanical controls of the swelling. This article presents a literature review of processes in swelling clay-sulfate rocks and associated controls. Numerical models that aim at simulating the processes and controls are also included in this review, and some of the remaining open questions are pointed out. By focusing on process related work in this review, the article intends to stimulate further research across disciplines in the field of swelling clay-sulfate rocks to finally get a step further in managing the swelling problem in geotechnical projects.

Keywords: swelling; clay-sulfate rocks; anhydrite; tunneling; review

1. Introduction

The swelling of clay-sulfate rocks causes severe problems in tunnel engineering (e.g., Einstein 1996; Anagnostou et al. 2010). It may result in a heave of the tunnel floor, destruction of the lining or uplift of entire tunnel sections and the land surface above (e.g., Anagnostou 1992). Well-known examples of tunnels with large swelling problems include tunnels in the Jura Mountains of Switzerland and France, and in the Stuttgart metropolitan area in South Germany (Steiner 1993; Berdugo et al. 2009a,b). In these examples, the swelling mainly occurs in clay-sulfate rocks of the Triassic Gipskeuper ("Gypsum Keuper") formation. Amstad and Kovári (2001) provided a comprehensive report that goes particularly into engineering details of tunnel planning and construction in such rocks. Also other formations with clay-sulfate rocks are affected. A prominent example is the Lilla tunnel in Spain, where swelling occurred in Tertiary clay-sulfate rocks (Alonso and Olivella 2008; Ramon 2014). Swelling problems are also reported from Saudi Arabia (Azam 2007), Poland, Italy and Texas/USA (Yilmaz 2001, and references therein). It is likely, although not known by the authors, that more cases exist elsewhere.

The swelling of clay-sulfate rocks is not only a thread in tunnel engineering, but also makes extensive and repeated repair work of high-performance roads (Kleinert and Einsele 1978) and bridges (Alonso and Ramon 2013) necessary. Another case, which recently attracted much public attention, is the case of Staufen (Southwest Germany). In this town, the installation of a geothermal heat pump system caused dramatic damage in the historic town center (Goldscheider and Bechtel 2009; Sass and Burbaum 2010; Sass and Burbaum 2012; Ruch and Wirsing 2013; Grimm et al. 2014). Swelling ground with uplift rates exceeding 1 cm/month after the drilling in clay-sulfate rocks of the Gipskeuper formation resulted in more than 250 houses being seriously damaged. Swelling problems associated with clay-sulfate rocks are likely to gain even more attention in the near future. The construction of a major railroad line that involves many kilometers of tunnels within the Gipskeuper formation started in the area of Stuttgart (Stuttgart 21; Bacharach 2007; Wittke 2007). In addition, damage to more than 100 houses has recently been observed in the town of Böblingen near Stuttgart. Similar to the case of Staufen, geothermal drillings are suspected to have triggered swelling in clay-sulfate rocks of the Gipskeuper formation, resulting in damaging ground heave (Grimm et al. 2014).

The swelling of clay-sulfate rocks may also have importance to other geoscientific applications. Underground storage of carbon dioxide (CO_2) in aquifers has been proposed for reducing the emission of greenhouse gases into the atmosphere (e.g., IPCC 2005; Lemieux 2011). Processes related to the swelling of clay-sulfate rocks may seriously affect the functionality of the storages' seal. For example, the clay-sulfate rocks of the Gipskeuper formation are considered to be a seal for CO_2 sequestered in the underlying Muschelkalk aquifer (Chevalier et al. 2010; Fabbri et al. 2013).

Referring to swelling in clay-sulfate rocks in tunneling, Leopold Müller-Salzburg noted in the third volume on tunneling of his fundamental text book on rock engineering that "a truly coherent explanation of these phenomena is still owing" (Müller-Salzburg 1978, p. 306). This valuation is still true after more than three decades of research in the field of swelling clay-sulfate rocks. To find engineering solutions to the swelling problem, time-pressure-heave relations could serve to predict the mechanical interaction between the swelling rock and the tunnel. While such a relation was established for pure clay rocks (Grob 1972; Madsen and Müller-Vonmoos 1989), a relation for clay rocks containing anhydrite is still lacking (e.g., Pimentel 2007a). This is especially problematic because clay-sulfate rocks develop larger swelling strains and higher swelling pressures than pure clay rocks (e.g., Madsen and Nüesch 1991; Wittke et al. 2004). However, it is questionable if a general stress-strain relation for swelling clay-sulfate rocks even exists, because the swelling behavior of such rocks is controlled by coupled hydraulic, chemical and mechanical processes that hardly can be reflected by a general swelling law. It is still an unsolved problem to predict the development of swelling strains or pressures for actual projects. A fundamental reason for our present inability to predict the swelling behavior of clay-sulfate rocks is the lack of a comprehensive understanding of the processes involved (Anagnostou et al. 2010).

It is self-evident that process understanding is the key to the current pressing research questions related to clay-sulfate swelling. Processes include geological, mineralogical, chemical, hydrological and mechanical processes. Hence, an understanding of the swelling processes needs interdisciplinary approaches. Moreover, to understand the swelling comprehensively, not only the processes involved in the swelling itself has to be addressed. Also other processes that – directly or indirectly – impact the swelling must be considered. In other words, in addition to the processes that are active during swelling, also the controls of these processes have to be addressed. This article reviews the current state of knowledge related to processes in swelling clay-sulfate rocks and the controls that impact clay-sulfate swelling, including numerical models that allow scientists and engineers to simulate these processes and associated controls. The review ends with an outline of open research questions and future work that still has to be done to get a step further in coping with the swelling problem.

Unfortunately, reviews can never be complete. Especially the history of case studies is not addressed here, as this has already been done elsewhere (for an overview see Steiner 1993; Amstad and Kovári 2001; Berdugo et al. 2009a,b). However, we believe to present relevant work that provides in-depth insights into the current scientific state of knowledge of processes and controls in swelling clay-sulfate rocks. Bringing together research across disciplines, the authors hope to stimulate scientific discussion and innovation to enhance our present knowledge of processes and controls in swelling clay-sulfate rocks; and to assess their implications for geoscientific planning of major engineering projects.

2. Processes and controls in swelling clay-sulfate rocks

2.1 Overview of swelling mechanisms

The swelling of clay-sulfate rocks may involve both "clay swelling" and "sulfate swelling" (Fig. 1). Clay swelling results from osmotic water inflow between the surfaces of neighboring clay minerals, increasing the distance between them. The osmotic water inflow is driven by concentration differences close to the clay surfaces and in the pore water (osmotic swelling; Madsen and Müller-Vonmoos 1989). In addition, clay swelling can result from hydration of the clay minerals, which means that water is incorporated in the crystal lattice between the silicate layers of the clay minerals (inner-crystalline swelling; Madsen and Müller-Vonmoos 1989). Clay minerals that have large potential for inner-crystalline swelling include smectites, such as montmorillonite (Krähenbühl et al. 1987) and corrensite (Lippmann 1976). Similarly to inner-crystalline clay swelling, sulfate swelling is caused by sulfate hydration ($CaSO_4$ + 2 H_2O = $CaSO_4$ • 2 H_2O). This transformation of anhydrite into gypsum does not take place directly, but indirectly via anhydrite dissolution and gypsum precipitation (e.g., Jeschke et al. 2001). In an open system, i.e., when water from outside the system is added to anhydrite, the reaction is accompanied by a volume increase of 61%. This volume increase can be calculated from balancing molar volumes of anhydrite and gypsum. It must be noted that the volume increase of the total (clay and sulfate) rock is smaller, because only a part of the rock consists of sulfate minerals (c.f., Fig. 1).

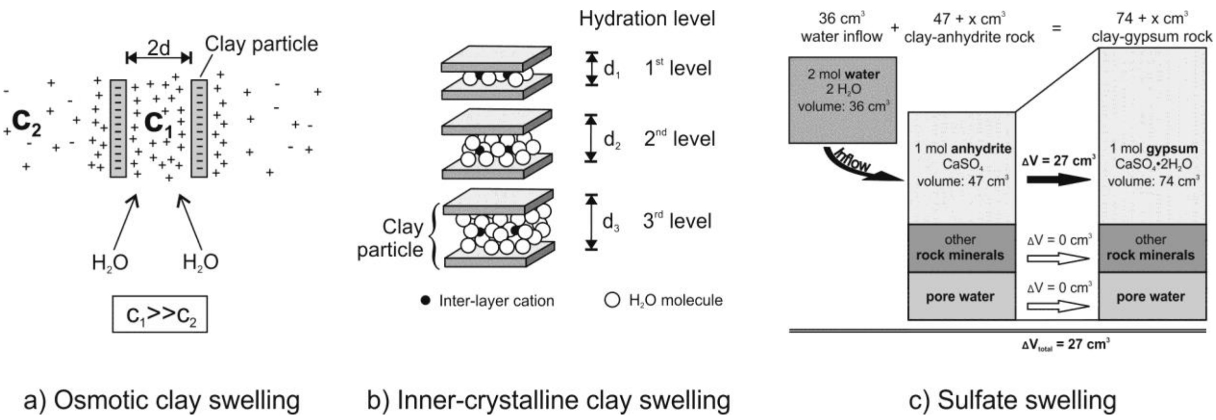

Fig. 1 Swelling mechanisms. a): Osmotic clay swelling (after Madsen and Müller-Vonmoos 1989). b) Inner-crystalline clay swelling (after Krähenbühl et al. 1987). c) Sulfate swelling (from Butscher et al. 2011a)

If volumetric swelling strain is prevented, considerable swelling pressures develop. Documented swelling pressures of anhydrite-bearing clay rocks show high variation. Maximum swelling pressures of the Gipskeuper formation documented in the literature, which are summarized by Anagnostou (1992), Steiner (1993), Hauber et al. (2005), and Berdugo et al. (2009a,b), range between 1.7 MPa and 16 MPa. These values were measured in the laboratory from samples of the Gipskeuper formation and in-situ within this formation. Locations include the Wagenburg, Freudenstein and Heslach tunnel in the Stuttgart metropolitan area in Germany and the Hauenstein, Hauenstein Basis and Belchen tunnel in Switzerland. A difference between laboratory and in-situ measurements can be recognized: while in-situ maximum swelling pressures do hardly exceed 5 MPa in the Gipskeuper formation (Steiner 1993), laboratory testing revealed swelling pressures up to 16 MPa (Henke et al. 1975, in Steiner 1993). This was also confirmed by Serafeimidis et al. (2015), who investigated scale-effects in the swelling of clay-sulfate rocks. The conclusion that swelling pressures in the field remain lower than those measured in the laboratory, however, is precarious, because long-term swelling pressures in the field are mostly unknown. Yet, having in mind the large variation of maximum swelling pressures measured in-situ and in the laboratory, it must be concluded that swelling pressures developing in clay-sulfate rocks are extremely difficult, if not impossible, to predict from past experiments, but must be expected to exceed the resistance of the tunnel reinforcement (about 1 MPa is technically and economically reasonable) by far.

2.2 Geological controls

Swelling phenomena are directly linked to certain geological formations. The majority of swelling problems in tunneling is reported from the Triassic Gipskeuper ("Gypsum Keuper") formation in southern Germany and northern Switzerland (Steiner 1993; Berdugo et al. 2009a,b). Henke and Kaiser (1975) noted that swelling in the Gipskeuper is further limited to certain sub-units of this formation, namely the "Mittlerer Gipshorizont" and the "Grundgipsschichten". Such observations illustrate that the stratigraphic position of a tunnel is one of the factors controlling the occurrence of swelling.

An explanation for the relation between the stratigraphic position and swelling is given by the typical mineralogical composition of stratigraphic units. Mineralogical controls are discussed in detail in the next section but, naturally, only units that contain both clay and anhydrite are subject to clay-sulfate swelling. Also the texture of the rock may be important. Due to the larger crystal-surface that can get in contact to water, finely dispersed anhydrite has a larger swelling potential than anhydrite veins and nodules; and massive beds of anhydrite do hardly swell (Rauh et al. 2006).

The configuration of geological units also determines the distribution of hydraulic properties in the subsurface and therefore controls water access to swellable rocks. Faults may further impact flow paths, as they may contain highly fractured zones as preferential pathways for groundwater flow (e.g., Caine et al. 1996). The position of a tunnel relative to geological units and faults is therefore an important control for rock swelling. The regional geological setting and its relation to the swelling of clay-sulfate rocks was analyzed in a study by Butscher et al. (2011b), indicating effects of tunneling on regional groundwater flow that may trigger rock swelling by favoring anhydrite dissolution and gypsum precipitation.

In clay-sulfate rocks, a "gypsum level" (GL) and an "anhydrite level" (AL) can often be observed (e.g., Murray 1964; Steiner 1993; Noher et al. 2010). The GL represents the border between the zone where sulfate is present as gypsum and the leached zone where all sulfates are dissolved away (i.e., no sulfate is present). In the leached zone, a gypsum karst may have developed with considerable amounts of groundwater and increased hydraulic conductivities. The spatial configuration of the GL is therefore expected to influence flow patterns and, hence, swelling. The AL represents the border between the zone where the occurring sulfate mineral is gypsum and the zone where the occurring sulfate mineral is mainly anhydrite. Water inflow into the anhydrite-bearing zone is critical for rock swelling. Hence, the position of a tunnel relative to the position of the AL controls the occurrence of swelling in tunneling. Such relations have been investigated by Butscher et al. (2011a), confirming that the position of the AL may impact the swelling. The relation between the geological framework and hydraulic controls is addressed later in section 2.5, presenting hydraulic controls in more detail.

2.3 Mineralogical controls

Rauh et al. (2006) investigated the swelling of pure anhydrite with the powder swelling test (Thuro 1993). In their study, samples of pure massive anhydrite were collected from different geological formations, characterized by different grain sizes ("crystallinity"). The anhydrite samples were ground to a homogeneous powder with a "defined grain size between fine sand and clay". It was observed that the powder samples obtained from fined grained anhydrite developed higher swelling strain in the swelling tests than samples obtained from coarse grained anhydrite. The authors argued that the grain size determines the specific surface of the mineral grains, with smaller grains having a larger specific surface. They confirmed this relation for the ground anhydrite powder by a specific surface analysis using the air permeability method after Blaine (DIN EN 196-6, 1990). The grain size of anhydrite in natural rocks depends on the rock's pressure and temperature history: Rocks that experienced large overburden (several km) contain coarser anhydrite crystals and show lower swelling potential. The authors of the study concluded that the swelling potential of pure anhydrite depends on the size of the mineral grains of the anhydrite, and thus on the former rock cover. However, it remains unclear to what extent the results obtained from anhydrite powder swelling tests can be transferred to the swelling behavior of clay-sulfate rocks.

It is a general observation that massive pure anhydrite layers (without clay present) do not develop considerable swelling (e.g., Madsen and Nüesch 1991, Steiner 1993, Madsen et al. 1995, Einstein 1996). This is explained with the relatively small area of the almost impermeable anhydrite that may be exposed to water, allowing water access only at the surface and in fissures. An additional process hampering the swelling of massive anhydrite is the forming of a protective gypsum coating from the reaction anhydrite to gypsum (passivation), preventing further transformation (Steiner 1993).

The role of clay swelling in clay-sulfate rocks is not yet entirely understood. Wittke et al. (2004) considered the contribution of clay swelling to the swelling of clay-sulfate rocks of minor importance in tunnel engineering, because developing swelling pressure resulting from clay swelling was relatively low. Comparing maximum swelling pressures of clay rocks with clay-sulfate rocks, Madsen and Nüesch (1991) concluded that clay-sulfate rocks develop 2 to 10 times higher swelling pressures than pure clay rocks. The compilations of the authors named in the sections above also support the observation that clay-sulfate rocks often develop considerably higher swelling pressures than pure clay rocks. These findings suggest that the swelling of clay-sulfate rocks is dominated by sulfate swelling.

The studies of Madsen and Nüesch (1991), however, point at a possibly important role of clay swelling in the swelling of clay-sulfate rocks. They clearly showed that the swelling potential of clay-sulfate rocks depends on the clay content of the rock (Fig. 2): While pure anhydritic rocks do not swell, the swelling potential of clay-sulfate rocks increases with clay content. Only at clay contents exceeding about 15%, the swelling potential decreases again. The increase of the swelling potential with the clay content is explained by the limited water access to the very low permeable anhydrite. In contrast to anhydrite, clay minerals allow water access by osmotic processes. This water access enables clay swelling, accompanied by disintegration of the rock (Madsen and Nüesch 1991; Nüesch et al. 1995). As a result of rock disintegration, water can access the anhydrite, leading to anhydrite swelling. This interpretation means that clay swelling is a prerequisite for anhydrite swelling. The decrease in swelling potential at higher clay contents is explained by lower anhydrite contents coming along with high clay contents (Madsen and Nüesch 1991). Bearing in mind the higher swelling potential of anhydrite compared to clay, and the fact that higher clay contents reduce the stiffness of the rock, the decrease in swelling potential at high clay contents is plausible.

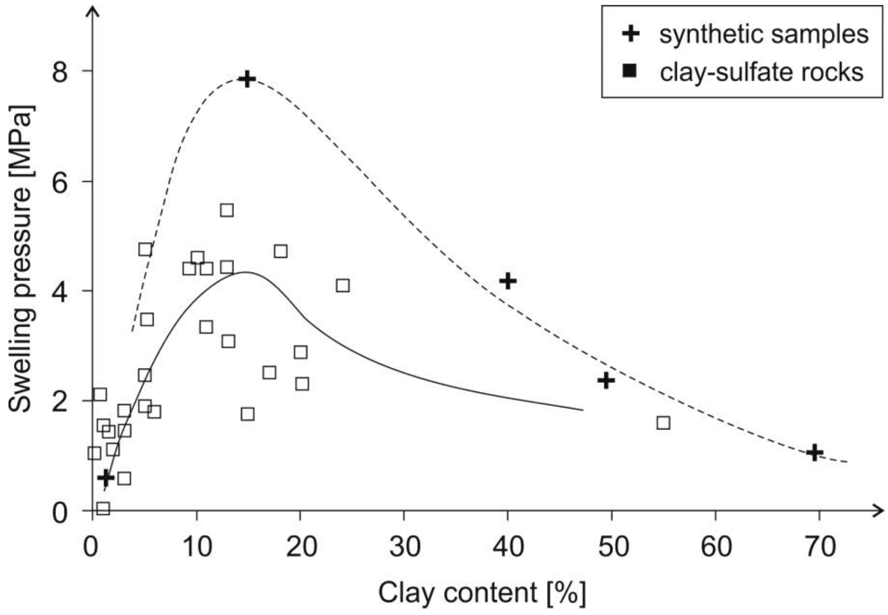

Fig. 2 Swelling stress vs clay content (after Hauber et al. 2005, with data from Madsen and Nüesch 1991)

Lippmann (1976) emphasized the role of the clay mineral corrensite in clay-sulfate swelling. This clay mineral is abundant in the Gipskeuper formation and has large potential for inner-crystalline swelling (Schlenker 1971). Lippmann (1976) argues that anhydrite in the presence of corrensite is indicative for corrensite being not fully hydrated, because anhydrite would be alternated to gypsum if enough water would be present for complete corrensite hydration. He suggests that anhydrite can be regarded as "desiccation agent", preventing corrensite from hydration. His corrensite-anhydrite theory describes how high water inflow caused by tunnel excavation initiates the hydration of corrensite, followed by slower anhydrite to gypsum hydration. The combination of these two processes may explain the high swelling potential of the Gipskeuper formation where both corrensite and anhydrite are present.

The role of clay in the swelling of clay-sulfate rocks was further discussed by Wichter (1989), Madsen and Nüesch (1990), Anagnostou (1992), Steiner (1993), and Hauber et al. (2005). Hypotheses can be summarized as follows:

(1) Clay swelling, preceding sulfate swelling, disintegrates the rock and creates water pathways to anhydrite.
(2) Clay minerals deliver water (crystal water or attached/adsorbed water) to anhydrite.
(3) Clay layers act as "micro aquifer" because they are more permeable than pure anhydrite layers.
(4) Clay minerals adsorb water, hindering water circulation and allowing for an increase of concentrations until gypsum saturation is reached.
(5) Clay minerals absorb water and, in doing so, increase sulfate concentrations in the remaining pore water until gypsum saturation is reached.
(6) Clay minerals act as chemical catalysts.

It can be concluded that the exact role of clay in the swelling of clay-sulfate rocks is still uncertain.

2.4 Chemical controls

Jeschke et al. (2001) have shown that the transformation of anhydrite into gypsum does not take place directly, but indirectly via anhydrite dissolution and gypsum precipitation. The conditions controlling dissolution and precipitation of the sulfate minerals, of course, strongly depend on the geochemistry of the pore water. This suggests that geochemical processes, in addition to hydrogeological processes, belong to the key factors controlling the swelling of clay-sulfate rocks. An understanding of the processes particular within the geochemical system $CaSO_4$-H_2O is therefore essential for understanding the swelling phenomena.

Basic research on the geochemical system $CaSO_4$-H_2O started in the 1920s. Partridge and White (1929) and Hill (1937) analyzed the effect of temperature on the solubility of gypsum and anhydrite. MacDonald (1953) calculated the equilibrium conditions of the system $CaSO_4$-H_2O. Marsal (1952) investigated the influence of pressure on this system and Corti and Fernandez-Prini (1984) analyzed the stability fields of sulfates over a wide temperature range. Other studies on this geochemical system include the studies by Blount and Dickson (1973) and Innorta et al. (1980).

Anhydrite dissolution and gypsum precipitation are controlled by the sulfate concentration in the pore water, the temperature, and the total pressure (Hill 1937; Marsal 1952; Hardie 1967; Blount and Dickson 1973). The total pressure may be exerted via the pore water or via the solid pressure between mineral grains. If these conditions are known, it is possible to determine the stable phase(s) of the sulfate minerals; and, if conditions change, which of the sulfates will dissolve or precipitate. Human activities, such as tunneling, can change the pressure conditions. In addition, induced hydraulic changes may change groundwater flow paths, and thus the origin of the groundwater and its geochemical composition. The combined analysis of pressure conditions and pore water geochemistry would allow one to assess if conditions are met to dissolve anhydrite and, at the same time, precipitate gypsum as a prerequisite for rock swelling. Such an analysis could also indicate formation waters that are critical with respect to rock swelling, if they inflow into clay-sulfate rocks after induced hydraulic changes under given temperature and pressure conditions.

The stability fields of gypsum and anhydrite in the system $CaSO_4$-H_2O determined by Marsal (1952) can explain the geochemical process of anhydrite dissolution and gypsum precipitation leading to swelling (Fig. 3). At concentrations above the equilibrium lines, the solid mineral phase is stable and precipitation of the respective mineral occurs. At concentrations below the equilibrium lines, the aqueous solution is stable and dissolution of the respective mineral occurs. Between the equilibrium lines of anhydrite and gypsum at temperatures lower than about 40 °C, anhydrite dissolves and, at the same time, gypsum precipitates (Fig. 3, shaded area). These conditions are critical with respect to swelling of clay-sulfate rocks, which will be explained in the following example. In Fig. 3, the geochemical evolution of groundwater flowing into the Gipskeuper from the Upper Muschelkalk and Lower Keuper is illustrated. Typical sulfate concentrations of groundwater in the Gipskeuper (km1), Lower Keuper (ku) and Upper Muschelkalk (mo) are plotted at a temperature of 15 °C. Groundwater inflowing from the Lower Keuper or Upper Muschelkalk into the Gipskeuper will dissolve anhydrite and therefore increase in sulfate concentration until concentrations are above the equilibrium line of gypsum. At this moment, gypsum starts to precipitate, leading to swelling. The sulfate concentration of the groundwater will not significantly decrease during gypsum precipitation (which would stop the swelling), because the groundwater is still undersaturated with respect to anhydrite, dissolving more anhydrite and providing sulfate for continuing gypsum precipitation.

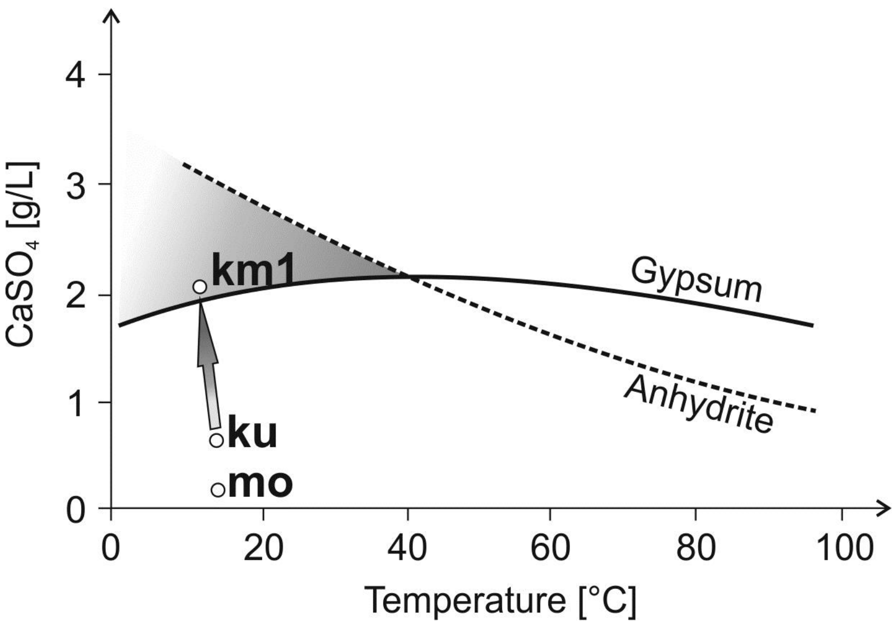

Fig. 3 Stability fields of gypsum and anhydrite in the system $CaSO_4$-H_2O (after Marsal 1952), depending on sulfate concentration and temperature (at 1 atm pressure). The shaded area indicates a zone where anhydrite dissolves and, at the same time, gypsum precipitates. Typical $CaSO_4$ concentrations in groundwater of the Upper Muschelkalk (mo), Lower Keuper (ku) and Gipskeuper (km1) are plotted from LGRB (2010). The arrow indicates the evolution of groundwater inflowing from the Lower Keuper into the Gipskeuper. Groundwater of the Lower Keuper in contact with anhydrite will dissolve anhydrite and increase in $CaSO_4$ concentration until conditions are met to precipitate gypsum, leading to swelling.

Although the early studies mentioned above determined the stability fields of gypsum and anhydrite under various concentration, temperature and pressure regimes, the kinetics of the reactions is also important to the swelling problem, because it cannot be assumed that the system is in equilibrium when swelling is triggered during tunneling. The kinetics of gypsum and anhydrite dissolution was investigated by Jeschke et al. (2001), Jeschke and Dreybrodt (2002) and Zorn et al. (2009). Jeschke and Dreybrodt (2002) determined in free drift batch experiments on anhydrite, using anhydrite particles of about 565 μm diameter, a rate constant for anhydrite dissolution k_A = 5.0E-6 mmol/cm²/s, corresponding to 6.8E-6 kg/m²/s, at T = 10 °C. Recent work investigating the reaction kinetics specifically in the light of swelling clay-sulfate rocks was taken on by Serafeimidis and Anagnostou (2012). They reviewed kinetic constants of the system anhydrite-gypsum-water and presented ranges of these parameters, with rate constants k_A for anhydrite dissolution between 2.4E-6 and 5.4E-6 kg/m²/s at T = 23-

25 °C and k_G for gypsum precipitation between 3.75E-7 and 5.35E-6 kg/m²/s at T = 20-30 °C. They also studied the effect of the initial size and shape of anhydrite and gypsum particles on the reaction kinetics by means of a parametric study with thermodynamic models.

A factor that complicates the assessment of geochemical processes in the swelling of clay-sulfate rocks is the presence of additional ions (in addition to calcium and sulfate) in the pore water. For example, high NaCl concentrations originating from sea salt lower the equilibrium temperature of gypsum and anhydrite by changing ionic strengths and reducing the activity of water (e.g., Marsal 1952; MacDonald 1953; Marshall and Slusher 1966; Blount and Dickson 1973). Also clay swelling can be affected by the presence of sea salt. Swelling experiments with distilled water and NaCl-saturated water with clay rocks and marls conducted by Hauber et al. (2005) showed that swelling strains are reduced in the presence of sea salt. This was explained by the reduction of osmosis. Though no experimental data was found that investigates the effects of sea salt on the swelling of clay-sulfate rocks, it is clear that the natural composition of the pore water containing many different ions has to be considered when geochemical processes affecting swelling are investigated.

A recent effort to calculate the solubilities and thermodynamic equilibrium of anhydrite and gypsum was undertaken by Serafeimidis and Anagnostou (2015). In contrast to the previous studies, they investigated the solubilities and thermodynamic equilibrium based on thermodynamic calculations specifically in the light of swelling clay-sulfate rocks. To this end, they accounted not only for the presence of foreign ions in the pore water, but also for the effect of clay minerals on the water activity and for surface energy effects depending on the pore size distribution. They showed that the clay in clay-sulfate rocks shifts the thermodynamic equilibrium between gypsum and anhydrite in favor of the stability of anhydrite. The reason for this shift is the reduction of the water activity in the presence of clay, and surface energy effects that become important at the typically small pore sizes in clay rocks. The authors presented a gypsum-anhydrite equilibrium diagram depending on pore water pressure, solid pressure (average pressure experienced by the mineral grains), temperature, water activity and pore size . In Fig. 4, the calculated equilibrium is indicated for different water activities at T = 15 °C and 1 atm pore water pressure, with gypsum being the stable phase above and anhydrite below the equilibrium curves. The figure illustrates the significant effect of the water activity on the equilibrium between gypsum and anhydrite. The authors also compared the predictions of their thermodynamic model with experimental results and literature data, finding good agreement. Their thermodynamic model was also used to explain the occurrence of anhydrite in the Gipskeuper formation at shallow depths (Anagnostou et al. 2015), where previous equilibrium models would rather predict gypsum as the stable phase.

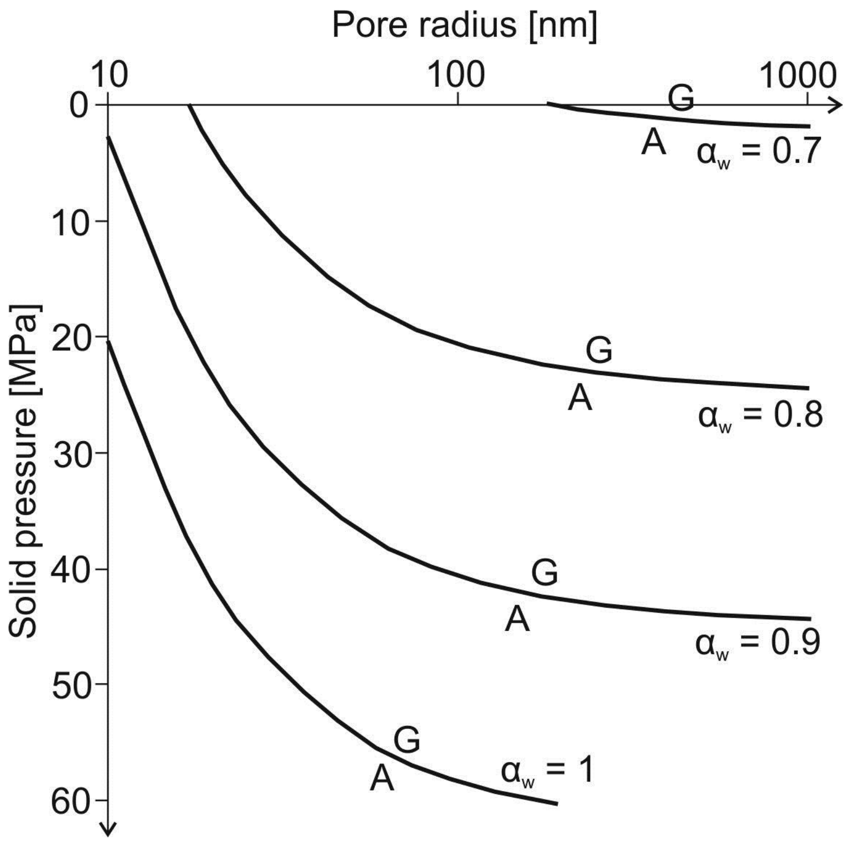

Fig. 4 Stability fields of gypsum and anhydrite (after Serafeimidis and Anagnostou 2015), depending on pore radius, solid pressure and water activity α_w (at T = 15 °C and 1 atm pore water pressure). $\alpha_w = 1$ denotes pure water (i.e., without foreign ions or interactions with clay minerals), $\alpha_w < 1$ indicates presence of foreign ions in the pore water and/or interaction with clay minerals. G: gypsum. A: anhydrite

Alonso (2011) and Ramon (2014) presented a conceptual model of swelling based on the geochemical process of gypsum crystal growth in fractures (Fig. 5). Because anhydrite is more soluble than gypsum at typical groundwater temperatures (see above), pore water in contact with anhydrite dissolves anhydrite until it becomes oversaturated with respect to gypsum. As a result, gypsum precipitates. Precipitation is facilitated when open space is available, such as (open) fractures. Gypsum crystals can nucleate on previously existing gypsum crystals or on surfaces of clay minerals. Fibrous gypsum ("satin spar") and gypsum needles in fractures growing perpendicular to the fracture walls were often observed in tunnels affected by clay-sulfate swelling as well as in laboratory experiments (e.g., Wichter 1989; Madsen and Nüesch 1990; Alonso and Ramon 2013; Alonso et al. 2013). Gypsum crystals growing perpendicular to the fracture walls can produce crystallization pressure and act similar to a lifting jack, pushing the fracture walls apart. Hence, developing swelling pressures theoretically can reach values corresponding to the crystallization pressure of gypsum.

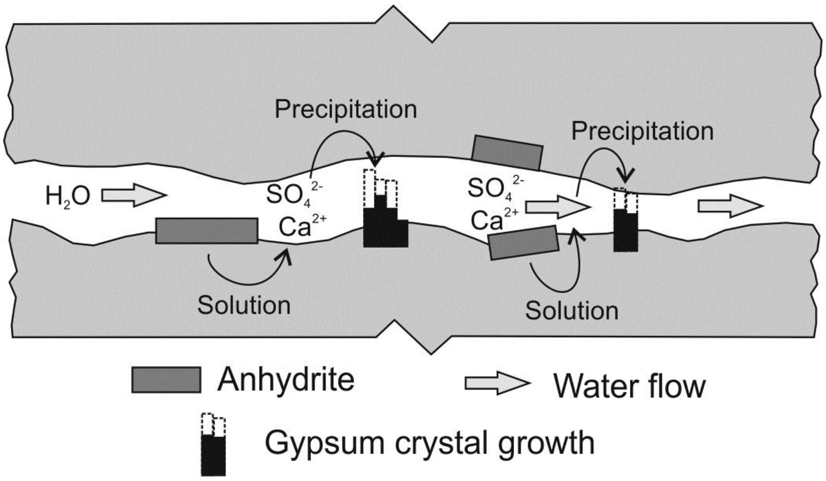

Fig. 5 Conceptual model for swelling by crystal growth (gypsum precipitation) (from Alonso 2011; Ramon 2014)

Flückiger et al. (1994) estimated theoretical swelling pressures from gypsum crystallization based on thermodynamical calculations presented by Xie and Beaudoin (1992). In these calculations, the crystallization pressure is proportional to the temperature and the natural logarithm of the solubility product ratio. The latter represents the ratio of the solubility of the solid mineral under pressure (crystallization pressure + atmospheric pressure) to the solubility of the solid mineral at atmospheric pressure. Flückiger et al. (1994) came up with a crystallization pressure of gypsum being 3.7 MPa at 20 °C. However, this value cannot explain the high swelling pressures of clay-sulfate rocks measured in laboratory and field experiments, many of them exceeding 4 MPa. According to Madsen et al. (1995), the study of Flückiger (1994) came up with gypsum crystallization pressures ranging between 3.7 MPa and 8.1 MPa, favoring a possible maximum swelling pressure for gypsum in the order of 6.5 MPa following geological considerations. These values match the majority of experimentally derived values. Only very high values exceeding 8 MPa cannot be explained. Hauber et al. (2005) mentioned that the theoretical thermodynamically calculated swelling pressure of gypsum is 20 MPa, referring to the study by Sahores (1962).

A very similar approach to thermodynamically calculate crystallization pressures was already presented by Winkler (1973). In his calculations, based on the work of Correns (1949), the crystallization pressure is proportional to the temperature and the natural logarithm of the ratio of the actual concentration of the solute during crystallization to the concentration of the solute at saturation. This ratio represents the distance of the pore water from saturation (oversaturation). At saturation, no crystallization pressure can be developed. At 15 °C, the swelling pressure of 3.7 MPa derived from Flückiger et al. (1994) corresponds to a 1.12-fold oversaturation of the pore water with respect to gypsum. Swelling pressures of 6.5 to 8.1 MPa (Flückiger 1994) and 20 MPa (Sahores 1962) correspond to 1.22 to 1.29 and 1.87-fold oversaturation, respectively, at 15 °C. When developing swelling pressures from gypsum crystallization are to be estimated based on such thermodynamical calculations, the degree of oversaturation of the pore water with respect to gypsum has to be known.

Considering the stability fields of gypsum and anhydrite at 15 °C (c.f., Fig. 3), it is reasonable to assume that the pore water cannot exceed a 1.5-fold oversaturation. At this temperature and one atmosphere pressure, the pore water is saturated with respect to gypsum if it contains 2 mg dissolved $CaSO_4$ per liter. The solution can dissolve anhydrite and increase in sulfate concentration until it reaches 3 mg dissolved $CaSO_4$ per liter. At this concentration, also anhydrite is stable in its solid phase, i.e., anhydrite is not further dissolved and sulfate concentrations in the pore water do not further increase. Accepting a maximum oversaturation of 1.5 in the pore water due to anhydrite dissolution, maximum swelling pressures of 13 MPa can develop from gypsum precipitation according to the calculation presented by Winkler (1973). This value matches observations made in swelling experiments (Steiner 1993) well. A prerequisite for the scenario of reaching 1.5-fold oversaturation is that anhydrite dissolution occurs faster than gypsum precipitation. The increase of sulfate concentrations in the pore water, however, can be hampered by gypsum precipitation as was shown by Jeschke and Dreybrodt (2002).

Serafeimidis and Anagnostou (2014) reviewed the approaches by Winkler (1973) and Flückiger et al. (1994) to thermodynamically calculate gypsum crystallizations pressures and developed them further. They pointed at some erroneous assumptions in the previous calculations and consider additional parameters that play an important role in developing crystallization pressures. Including the presence of foreign ions and clay minerals, which reduce the activities of the reactants, and also including the liquid-solid surface energy, which depends on the pore size and shape, they came up with a gypsum crystallization pressure being one order of magnitude higher than estimated in the previous studies. Taking realistic values for the ionic composition of the pore water, water activity and the pore size distribution, they estimated the gypsum crystallization pressure between 20 and 54 MPa at a temperature of 20 °C. Such high swelling pressures at the pore/crystal scale are reduced at larger scales (rock specimen, tunnel) because of interactions between the gypsum crystals and the rock mass and because developing pressures can be relieved by swelling heave (Serafeimidis et al. 2015). Taking such scale effects into account, the swelling pressures typically measured in the laboratory and in-situ, hardly exceeding 10 MPa, can be well explained.

Another recent study relating swelling pressures in clay-sulfate rocks to the crystallization pressure of gypsum was conducted by Ramon and Alonso (2014). Similar to the study by Serafeimidis and Anagnostou (2014), their theoretical approach considered both the thermodynamical equilibrium between the solute and precipitating gypsum, and the surface energy at the interface between the solution and crystals, the latter depending (amongst others) on the pore geometry. They derived a theoretical swelling pressure of 8.6 MPa for cylindrical pores and found reasonable agreement with field observations in the Lilla tunnel in Spain, where measurements with pressure cells between the lining and the rock indicated swelling pressures up to 6.7 MPa (Ramon and Alonso 2014).

The theoretical studies by Serafeimidis and Anagnostou (2014) and by Ramon and Alonso (2014) currently represent the most advanced approaches to quantitatively explain developing swelling pressures in clay-sulfate rocks arising from gypsum crystal growth. Other recent and fundamental research on crystal growth and resulting pressure, but without directly relating to the swelling of clay-sulfate rocks, includes for example the studies of Scherer (2004), Steiger (2005a,b) and Flatt and Scherer (2008). In these studies, thermodynamic equations are provided to calculate crystallization pressures, accounting for various factors such as capillary effects, evaporation, wetting-drying cycles and cement hydration (Scherer 2004); crystal size, pore size and pore entrance size (Steiger 2005a,b); and hydrostatic tensile stresses (Flatt and Scherer 2008).

2.5 Hydraulic controls

Groundwater flow in clay-sulfate rocks is a combination of flow along discontinuities (bedding planes, fractures, joints) and flow within the porous rock matrix between the discontinuities (e.g., Sahimi 2011). According to Wittke (2014), under natural conditions, clay-sulfate rocks can be found as initially "dry" in the Gipskeuper because of the low permeability of the rock (hydraulic conductivity in the order of 5E-14 m/s; NAGRA 2002). Tunnel excavation and the resulting unloading leads to opening of discontinuities and allows for fracture flow. After saturation of the fractures, the porous rock matrix starts to become saturated by the process of capillary water absorption (Wittke 2003, 2014). The latter can be described by a diffusion process (e.g., Kahr et al. 1985). Hence, the access of water to swellable rocks is controlled by both fracture flow in the fractured rock mass and by the water absorption capacity of the intact rock.

As explained in the previous sections, the processes involved in swelling require water access. Thus, hydrogeological processes must play a dominant role in the swelling of clay-sulfate rocks. Consequently, Butscher et al. (2011a,b,c) proposed that changes in groundwater flow systems, caused by tunneling, trigger the swelling. They investigated the impact of tunneling on groundwater flow systems and implications for the swelling of clay-sulfate rocks.

In the study of Butscher et al. (2011c), an approach to estimate the swelling risk at the Chienberg tunnel is presented. This study investigated the hydrogeological conditions of four zones of this tunnel crossing the Gipskeuper formation. In two of the zones, heavy swelling occurred after tunnel excavation, while in the other two zones swelling does not occur to date. The geological conditions of these zones were analyzed using field data from exploration boreholes and geological documentation during tunnel excavation. In addition, groundwater flow systems before and after tunneling were investigated based on numerical modeling. The study revealed that, in certain situations, the tunnel and its surrounding excavation damaged zone (EDZ) provide a "hydraulic short circuit" between the weathered Gipskeuper and the anhydrite-bearing strata of the non-weathered Gipskeuper (Fig. 6). It could be shown that, as an effect of tunnel excavation, water from the weathered Gipskeuper above the tunnel gets in contact with anhydrite at the tunnel invert. The study suggests that this hydrogeological process triggers the transformation of anhydrite into gypsum and, thus, rock swelling.

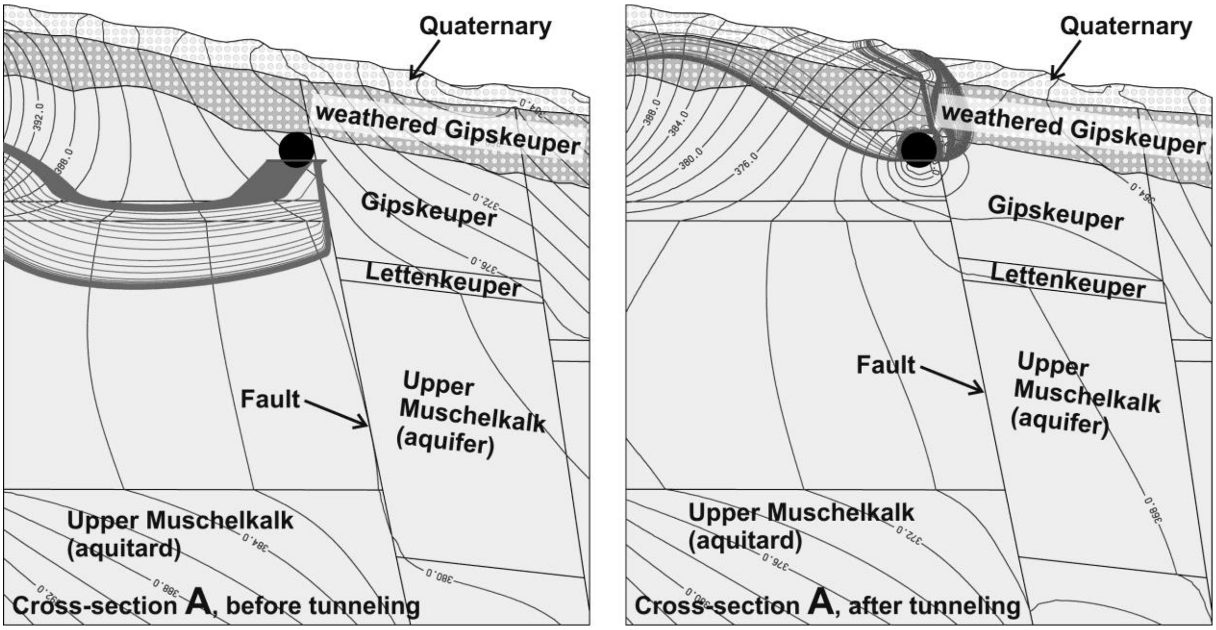

Fig. 6 Flow paths towards anhydrite-bearing layers before (left) and after tunneling (right). After tunnel excavation, the anhydrite level is hydraulically connected to the weathered Gipskeuper by the tunnel and the surrounding EDZ (from Butscher et al. 2011c)

Evaporation at the tunnel sidewalls was also proposed as possible hydrological mechanism leading to swelling (Anagnostou 1995; Alonso and Olivella 2008). Evaporation can increase the sulfate concentration in pore water until super-saturation, leading to gypsum precipitation and, hence, swelling. Alonso and Olivella (2008) described and simulated evaporation driven swelling in the Lilla tunnel in Spain. Alonso et al. (2013), however, pointed out that the mass of gypsum required to match observed floor heave in this tunnel cannot be derived only from this process. This is in accordance with the findings of Anagnostou (1995), who investigated the influence of evaporation at the tunnel walls and the crown on swelling in a numerical parametric study. He found that, except for very high relative humidity (> 90 %) in the tunnel, swelling strains due to evaporation are negligible.

2.6 Mechanical controls

Steiner (1993, 2007) and Steiner et al. (2010) proposed brittle failure of the rock after tunnel excavation to be a major process leading to rock swelling. They argue that before tunneling, swelling is prevented by high horizontal stresses due to over-consolidation (e.g., Kulhawy et al. 1989) of the rock. After excavation, stresses are reduced around the excavation to a value lower than the crystallization pressure of gypsum, enabling gypsum precipitation and, thus, swelling. Steiner et al. (2010) argue that swelling therefore depends on stress conditions in the subsurface, but also on excavation and construction procedures that control the stress redistribution after tunneling. They also presented case histories of tunnels in swelling clay-sulfate and combined observations with numerical models that simulate stress states to show the important role of brittle fracture development in swelling (Steiner et al. 2011).

Similarly, Amann et al. (2010) proposed brittle failure of the rock as mechanism triggering swelling. Based on numerical models and data from tunnel projects in Switzerland, they showed that extensional fractures beneath the tunnel invert, generated by stress redistribution due to tunneling, provide a remarkable extension of a water conductive zone around the excavation. The generation of such water conductive zones has large potential to trigger the swelling of clay-sulfate rocks. This argumentation is in line with the hydrogeological considerations by Butscher et al. (2011a,c) that emphasize the role of the EDZ in swelling. Amann et al. (2014) also conducted laboratory experiments that investigate crack initiation and crack propagation in clay-sulfate rocks. Their results explain the creation of extensional fractures around the tunnel that promote swelling by gypsum crystal growth in these fractures.

Anagnostou (1993) pointed at the rock strength being an important parameter of the swelling mechanism. In this study, he presented a model for swelling rock in tunneling, where seepage flow coupled with elasto-plastic deformation is considered (c.f., section 2.7). With respect to the mechanical behavior of the rock, the model illustrated that swelling only in combination with limited rock strength (represented by the cohesion) can account for the large heaves often observed at the tunnel floor.

The swelling of clay-sulfate rocks leads to geomechanical processes that may result in heave of the tunnel invert, destruction of the lining or uplift of the entire tunnel section (Fig. 7). A swelling law stating a heave-pressure-time relation for clay-sulfate rocks would allow predictions about the mechanical behavior of swelling rock. For pure clay rocks, there is a linear relation between the swelling heave (strain) and the logarithm of pressure (Fig. 8) (Grob 1972; Madsen and Müller-Vonmoos 1989). A generally accepted relation for clay-sulfate rocks, however, is still lacking to date.

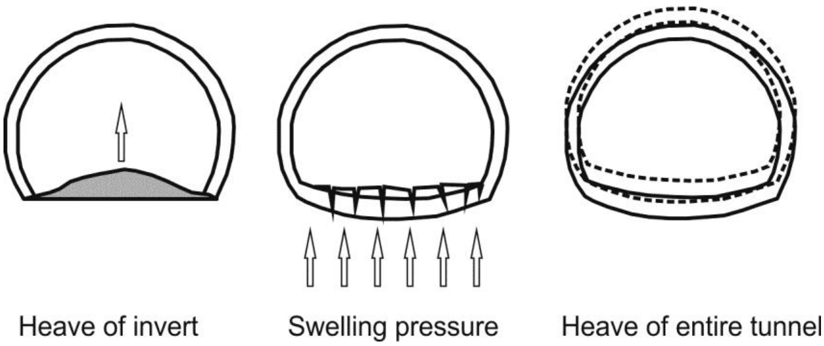

Fig. 7 Engineering problems in swelling clay-sulfate rocks **(**from Anagnostou 1992)

Madsen and Nüesch (1991), Nüesch et al. (1995) and Nüesch and Ko (2000) focused on time-swelling relations and maximum swelling pressures depending on the mineralogical composition of the rock. A relation between swelling heave and pressure, however, was not suggested. Grob (1972) proposed the linear relation between heave and the logarithm of pressure ("semi-logarithmic swelling law") not only for clay rocks, but also for clay-sulfate rocks. Pimentel (2007a,b), however, presented laboratory experiments indicating that the semi-logarithmic swelling law is inadequate for describing the swelling of clay-sulfate rocks. The laboratory tests revealed three different stages in the swelling process, including minimal deformation and prevented gypsum crystallization at high pressures (> 6 MPa); large increase in deformation due to gypsum crystallization at reduced pressures (4 to 5.5 MPa); and large but only small additional deformation, possibly along with gypsum dissolution, at low pressures (< 4 MPa) (Fig. 9). He pointed at a "tri-linear" relation to describe the different stages. A trusted swelling law that would describe the relation between swelling deformation and pressure, however, could not be found due to the relatively small number of swelling experiments and the fact that none of the experiments reached final (equilibrium) conditions within the observation time. Kirschke (1995) generally doubts the existence of a fixed relation between swelling strain and (final) pressure. According to him, swelling pressures and their temporal development are controlled by water inflow into the rock, which cannot be reflected by general strain-stress relations. Nevertheless, a clear trend can be observed in all swelling experiments with clay-sulfate rocks. The trend indicates that high pressures go along with small deformation, while low pressures go along with large deformation.

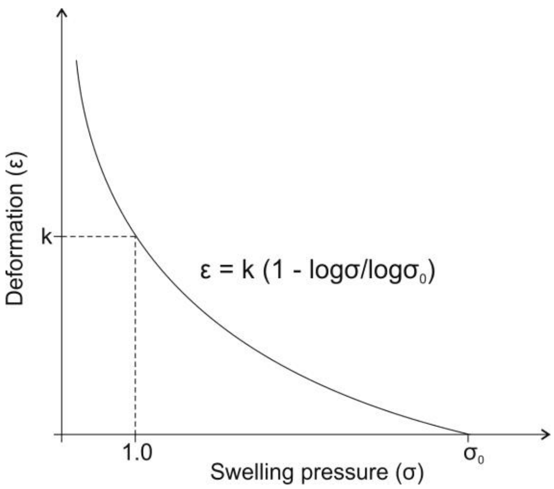

Fig. 8 Swelling law by Grob (1972)

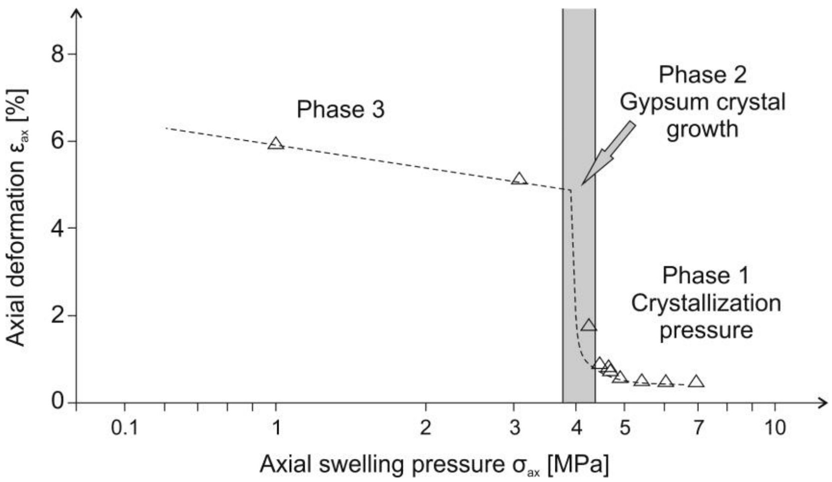

Fig. 9 Swelling test after Pimentel (2007b) showing a „tri-linear" swelling behavior

Based on the observation that low pressures are correlated with high deformation, and vice versa, engineering measures to counteract the swelling problem either aim at reducing swelling heave by opposing a mechanical resistance (rock anchors, reinforced lining, etc.), or reducing swelling pressure by allowing deformation. The former is referred to as the "resistance principle", while the latter as the "yield principle" (Pierau and Kiehl 1995). Kovári and Chiaverio (2007) combined both principles in the Chienberg tunnel by using both rock anchors and yield elements. In doing so, swelling pressures could be controlled while limited heave in a deformable zone under the tunnel was accepted (Fig. 10). Nevertheless, finding appropriate counter measures for an actual tunneling project affected by swelling remains extremely difficult. Successful engineering measures are hampered by the fact that a generally accepted swelling law does still not exist for clay-sulfate rocks, making predictions of heave and pressure impossible.

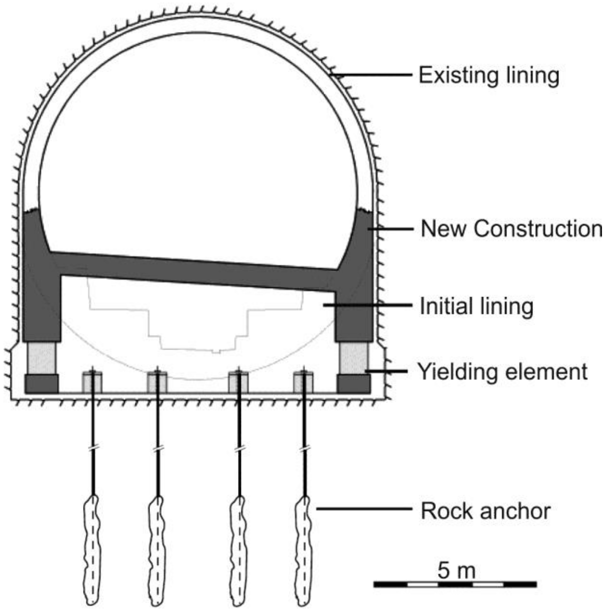

Fig. 10 Scetch of tunnel design in the Chienberg tunnel combining resistance to swelling by rock anchors with yield to swelling by deformalble elements to prevent heave of road surface (from Kovári and Chiaverio 2007)

2.7 Coupled processes

Flow through the rock mass and its mechanical properties are linked through their effects on each other. The physical interaction between hydraulic and mechanical processes is known as hydro-mechanical (HM) coupling (e.g., Neuzil 2003; Rutqvist and Stephansson 2003). HM coupled processes are further complicated by chemical processes and temperature effects. To understand the swelling processes comprehensively, the coupling of hydraulic, mechanical and chemical (HMC) processes has to be considered. Stephansson et al. (2004) provide detailed insights into the fundamentals, modelling, experiments and applications of coupled thermo-hydro-mechanical-chemical (THMC) processes in geological systems. An important coupled process to consider in swelling clay-sulfate rocks is the dissolution and precipitation of minerals changing the hydraulic (e.g., hydraulic conductivity, porosity) and the mechanical properties (e.g., strength, deformability) of the rock mass, and vice versa.

The effect of THMC coupled processes in the swelling of clay-sulfate rocks is still not well understood. Most of the theoretical and experimental investigations related to rock swelling reported in the literature focus on the mechanical behavior of the material (e.g., Bellwald and Einstein 1987; Barla 2008; Amann et al. 2010). Anagnostou (1992, 1993, 1995) was the first to consider HM coupled processes in order to investigate the effect of seepage flow on the deformation pattern around tunnels in swelling rocks. Wittke (2003) and Wahlen (2009) presented a model that couples fracture flow with the closure of fractures by the swelling process. Wittke (2014) describes a low permeability layer that can often be found directly under the anhydrite level. He explains this phenomenon by a self-sealing mechanism. After swelling is initiated by water access, the swelling of the rock results in the closure of discontinuities, which in turn leads to prevention of further water inflow. Hence, swelling may stop soon after its initiation. Under natural conditions (not disturbed by tunneling), water access to clay-sulfate rocks could be prevented for long periods by this HM coupled process.

Alonso and Olivella (2008) proposed a chemo-mechanical model for evaporation driven crystal growth in rock fractures. Oldecop and Alonso (2012) presented a one-dimensional HMC coupled model to describe swelling deformation in a tunnel in Spain, and Ramon and Alonso (2013) and Ramon (2014) presented a HMC coupled model to assess the heave of pillars of a railway bridge in two dimensions. The latter studies are the only studies reported in the literature that consider HMC coupled processes (c.f., section 3). However, these studies do not account for the actual geological configuration and groundwater flow conditions at the field scale, e.g. in the way presented by Butscher et al. (2011a,b,c). The coupled consideration of thermal, hydraulic, chemical and mechanical processes is a promising approach that requires more attention in future studies.

3. Numerical models

To simulate the swelling of clay-sulfate rocks and the effects of the controlling coupled processes, a few numerical finite element models (FEM) have been developed and applied, in particular to address the swelling in various tunnels in Germany, Switzerland and Spain (Table 1).

The relation between swelling heave and the logarithm of pressure proposed by Grob (1972) was primarily implemented in most of these FEM simulating the mechanical swelling behavior. To this end, the swelling law by Grob (1972), considering swelling in only one dimension, was generalized for two and three dimensions (2D, 3D) by Anagnostou (1992, 1995) and Wittke-Gattermann (1998). Anagnostou (1992, 1993) developed the HM coupled model HYDROMEC in order to investigate the effect of seepage flow on the deformation pattern around tunnels in swelling rocks (Table 1). The 3D-implementation of the swelling law coupled with seepage flow was also performed with the finite element model FEST03 (Wittke 2003), additionally using a "water uptake coefficient" D_W. The coefficient D_W uses the diffusion equation (by its shape). However, it is not a diffusion coefficient but rather represents the water transport and the transformation of anhydrite into gypsum, i.e. crystallization of gypsum. The model was calibrated in the test gallery at the Freudenstein tunnel in Germany showing reasonable agreement between measured and simulated heave rates over a time period of 20 years (Wahlen and Wittke 2009). Considering the amount of input parameters (in total 11 parameters) and the degrees of freedom (4 parameters), it is still an ambiguous problem providing reasonable best fits, but may not reproduce all controlling processes.

Table 1 Numerical models available to study the swelling of clay-sulfate rocks

Code name	Numerical method	Availability	Processes[1]	Comments	Applications	References
FEST03	FEM	In-house	H ↔ M	Implementation of stress-strain laws for swelling rocks (SWELL1) after Grob (1972)	Model calibration in the test gallery at the Freudenstein tunnel (Wahlen and Wittke 2009)	Wittke (1978, 1990, 2014)
HYDROMEC	FEM	Scientific	H ↔ M	Implementation of a logarithmic stress-strain law including seepage flow (Darcy flow)	Hypothetical tunnel excavations in a swelling rock (Anagnostou 1992, 1993,1995)	Anagnostou (1992, 1993)
CODE_ BRIGHT	FEM	Scientific	T ↔ H ↔ M ↔ C	Implementation of gypsum crystal growth in a standard HM formulation for saturated porous media	Floor heave in the Lilla tunnel (Alonso and Olivella 2008; Oldecop and Alonso 2012). Heave of a railway bridge (Ramon and Alonso 2013; Ramon 2014)	Olivella et al. (1994, 1996)
TALPA	FEM	Commercial	H ↔ M	Implementation of stress-strain laws for swelling rocks (SWELL1) after Grob (1972)	Hypothetical tunnel excavation in swelling bedrock (Heidkamp and Katz, 2004)	Heidkamp and Katz (2002)
PLAXIS	FEM	Commercial	T ↔ H ↔ M	Implementation of three different swelling laws based on Grob (1972)	Heave in the city of Staufen due to the installation of borehole heat exchangers (Benz and Wehnert 2010, 2012)	Benz and Wehnert (2010, 2012), Schädlich et al. (2013)

[1] H: hydraulic; M: mechanical; T: thermal; C: chemical; H ↔ M: hydro-mechanical coupled model; M ↔ C: mechanical-chemical coupled model; etc.

Currently, two commercial codes (TALPA and PLAXIS) are available, which both implemented 3D generalizations of the swelling law proposed by Grob (1972). Because this swelling law does not include the time, these models are generally not well suited to provide reasonable estimates of the temporal development of the swelling process. Benz and Wehnert (2010, 2012) applied the code PLAXIS to simulate the heave in the city of Staufen, which occurred after the installation of borehole heat exchangers in the Gipskeuper formation. The results of their simulations also indicated that temporal predictions of swelling heaves are still prone to large uncertainties.

Alonso and Olivella (2008) used a different approach to simulate the swelling of clay-sulfate rocks. They were the first providing a chemically and mechanically coupled model for swelling (c.f., Fig. 5), implementing gypsum crystal growth into the CODE_BRIGHT (Olivella et al. 1996). They effectively applied the FEM to simulate the temporal development of the floor heave in the Lilla tunnel. Furthermore, Alonso and Ramon (2013) and Ramon (2014) applied the model to the heave of the central pillars of a railway bridge. The model proved to accurately predict the mid-term heave of the central pillars. The results pointed out the importance of the initial anhydrite content, which primarily controls the intensity of expansion. Temperature effects are also essential in this model due to their influence on the equilibrium concentrations of gypsum and anhydrite. The setup of thermo-hydro-mechanical-chemical (THMC) coupled models is promising and should be further developed to provide a better understanding of the swelling processes and, thus, hopefully also improving future predictions.

4. Future work

This article reviewed the present state of knowledge about processes in swelling clay-sulfate rocks and the controls that impact such processes. Bringing together the research on this topic so far also revealed gaps that remain open and limit a comprehensive understanding of the swelling. This concluding section intends to point at remaining research questions and suggests some future work that still has to be done.

4.1 The role of clay in clay-sulfate swelling

Previous studies showed a clear relation between clay content of clay-sulfate rocks and the magnitude of swelling (Madsen and Nüesch 1991). Possible processes that would explain this observation were proposed (c.f., section 2), however, clear evidence that would support one or the other of the different processes, or that would quantify the individual contribution of the processes, is still lacking. Better understanding the role of clay minerals in swelling could possibly explain why swelling is in particular a problem in the Triassic Gipskeuper formation and much more rarely in other formations containing anhydrite; and why swelling does not occur every time engineering activities are undertaken in the Gipskeuper formation.

4.2 Gypsum crystal growth

The idea of gypsum crystal growth as conceptual model to explain macroscopic swelling of clay-sulfate rocks by microscopic processes was explicitly presented for the first time by Alonso (2011) (c.f., section 2.4). This idea was very fruitful in inspiring innovative research related to gypsum precipitation and its impact on the swelling process (e.g., Alonso and Ramon 2013; Serafeimidis and Anagnostou 2014, 2015). However, processes that control anhydrite dissolution and gypsum crystal growth have to be further addressed. This includes, for example, the dependency of these processes on groundwater flow in an open system. In addition, models that describe gypsum crystal growth have to be further developed in the future. Approaches already known from other disciplines (e.g., Bons and Jessell 1997; Means and Li 2001; Steiger 2005a,b; Noiriel et al. 2010; Wendler et al. 2011), which are beyond the scope of this review, could be a promising way for continuing research in this field.

4.3 Swelling law for clay-sulfate rocks

Time-heave-pressure relations are needed for optimal tunnel design in swelling ground. However, a generally accepted relation between swelling heave and swelling pressure does not exist yet (c.f., section 2.6). A major problem in finding such a relation is the fact that swelling experiments using oedometers last extremely long before equilibrium is reached; and that laboratory and field measurements often lead to different results. It is still impossible to derive parameters from swelling tests that would allow engineers to make reliable long-term predictions of the swelling behavior as a basis for the tunnel design. More experiments, both in the laboratory and in-situ, are required to provide a broader data basis for the development of a trusted time-heave-pressure relation.

4.4 Coupled processes

Hydraulic, chemical and mechanical processes, together with geological and mineralogical constraints, exercise control over the swelling. Addressing the interplay between these processes and controls is one of the most challenging tasks for future work in the field of swelling clay-sulfate rocks (c.f., section 2.7). With respect to hydromechanical coupled processes, it is unclear if swelling leads to additional flow paths for groundwater flow by inducing fractures and disintegrating the rock mass, which would favor further swelling, or if swelling leads to closing of fractures and sealing of existing flow paths, which would counteract the swelling. A lack of knowledge also exists with respect to hydraulic-chemical coupled processes. While anhydrite dissolution enhances groundwater flow by providing additional pore space, gypsum precipitation may reduce it by filling existing pore space. The quantification of changes in hydraulic conductivity during sulfate dissolution and precipitation requires future research. Also chemo-mechanical coupled processes, for example the effects of anhydrite dissolution and gypsum precipitation on geotechnical parameters of the rock mass, have not been quantified so far. The interplays between hydraulic, chemical and mechanical processes and controls finally need to be integrated in process based THMC coupled numerical models that can simulate the macroscopic effects of swelling for real case studies in geotechnical engineering.

4.5 Experimental work

Presently, experiments on swelling clay-sulfate rocks are mostly limited to swelling tests. Such experiments include free swelling and oedometer tests in the laboratory and the use of extensometers and pressure cells between the rock and the tunnel liner in-situ (e.g., Huder and Amberg 1970; ISRM 1999). The focus of these experiments is the observation of swelling heave and pressure and its temporal evolution. Further experimental work included irrigation and drainage measures; and testing of tunnel profiles and their impact on swelling damages (e.g., Fecker 1995; Amstad and Kovári 2001). Additional innovative field and laboratory experiments are needed that better address the processes underlying the swelling. Such experiments could include, for example, the measurement of changes in hydraulic and geotechnical behavior of the rock mass and geochemical conditions during swelling; and analyses that link mineralogical and petrological rock properties with swelling phenomena.

4.6 Final remarks

Great research efforts are still necessary to get a step further in responding to the swelling problem in geotechnical engineering practice. We believe that an understanding of the processes and controls in swelling clay-sulfate rocks is the key to finally finding sustainable solutions. The diversity of processes and controls involved in the swelling of clay-sulfate rocks makes multi-disciplinary approaches necessary. With this review, the authors hope to contribute to the ongoing scientific discussion about processes and controls in swelling clay-sulfate rocks and stimulate further innovative and transdisciplinary research.

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