Revista Épsilon N.º 12: 39-53 / enero - junio de 2009

Tunnelling and Swelling in Triassic Sulphate-Bearing Rocks. Part II -Case studies from Jura Mountains

Iván Rafael Berdugo De Moya* / Eduardo Alonso Pérez de Ágreda**
Enrique Romero Morales*** / Antonio Gens Solé****

Fecha de envío: 12 de diciembre de 2008.
Fecha de aceptación: 2 de marzo de 2009.

Abstract

Part II of this series of paper deals with the phenomenology of swelling in tunnels from Jura Mountains (Switzerland) excavated through the Gipskeuper and the Anhydritgruppe. The main features of expansions observed in the presented case studies are summarized and the performance of resisting and yielding support systems is compared. Evidences presented in this series of papers indicate that the transformation of anhydrite into gypsum is not a reasonable explanation for long-term expansive phenomena occurring in sulphate-bearing rocks. It is suggested that these phenomena are strongly related to rock degradation due to both tunneling induced drainage towards the bottom of excavations and tunneling induced ventilation.

Key words: sulphate-bearing rocks, Gipskeuper, Anhydritgruppe, swelling, tunnel, Jura Mountain, degradation, drainage, ventilation.

Construcción de túneles y expansión de rocas triásicas sulfatadas. Parte II: estudio de caso de las Montañas Jura

Resumen

La Parte II de esta serie de artículos trata sobre la fenomenología de las expansiones en túneles de Jura Mountains (Suiza) excavados a través del Gipskeuper y del Anhydritgruppe. Se resumen los principales aspectos de las expansiones observadas en los casos de estudio presentados y se compara el funcionamiento de sistemas de soporte resistente y deformable. Las evidencias presentadas en esta serie de artículos indican que la transformación de anhidrita en yeso no es una explicación razonable para los fenómenos expansivos a largo plazo que ocurren en rocas sulfatadas. Se sugiere que esos fenómenos están estrechamente relacionados con la degradación de las rocas debido tanto al drenaje hacia el fondo de la excavación como a la ventilación inducida por la construcción de túneles.

Palabras clave: rocas sulfatadas, Gipskeuper, Anhydritgruppe, expansión, túnel, Jura Mountain, degradación, drenaje, ventilación.

* Researcher, Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia. ivan.berdugo@upc.edu
** Professor, Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia. eduardo.alonso@upc.edu
*** Geotechnical Laboratory Director, Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia. enrique.romero-morales@upc.edu
**** Professor, Department of Geotechnical Engineering and Geosciences, Technical University of Catalonia. antonio.gens@upc.edu

Introduction

The characterization of the main phenomenological aspects of expansions in sulphate-bearing rocks has an enormous importance to identify the mechanisms underlying the swelling, their triggering events and the causes of heave and swelling pressure exhaustion. This paper deals with the phenomenology of swelling in tunnels excavated through Triassic anhydritic-gypsiferous claystones from the Anhydritgruppe and the Gipskeuper, in particular with the swelling-time relationships.

Fundamentals of the principles of resisting and yielding support applied to rock swelling affecting tunnels are presented and selected case studies — including tunnels and test galleries, are presented. The theme is tackled covering a spectrum of cases initiating with those located in Baden-Württemberg (Germany) and concluding with experiences gained in tunnels from Jura Mountains (Switzerland).

In each one of the exposed cases the most important construction and operation aspects are described and their possible effects on rock swelling discussed. Special attention is given to rock-groundwater-environment interaction conditions under which the compiled phenomenology was observed as well as to indicators of chemo-mechanical degradation of implicated rocks.

This work is the result of comprehensive analyses of data on tunneling in Germany and Switzerland that were carried out as a part of the research project "Anhydritic Claystones and their Impact on Public Works", developed by the consortium CIMNE-Department of Geotechnical Engineering and Geosciences (UPC) with the financial support of the Spanish Ministry for Infrastructures.

Case studies from Jura Mountains

In Switzerland tunnels affected by the most severe expansive phenomena are located in Jura Mountains and in the prealpine hills (Grob, 1976). The geological formations involved in these cases are materials from the Triassic (anhydrite-Keuper marl), the Jura (Lias, marl of lower Dogger; Opalinus claystone) and the complex Molasse (marls of the lower and the upper fresh water levels). Figure 23 indicates the location of some tunnels selected for this research in order to examine the main mechanisms related with the swelling of sulphate-bearing rocks combined with other expansive clayey rocks.

Some of these tunnels were affected by expansive phenomena both during construction and during operation since the late 19th century. The phenomena, as well as technical solutions for design and repair of these tunnels were recently compiled and analyzed by Kovári & Descoeudres (2001) and Amstad & Kovári (2001) in two publications sponsored by the Swiss Tunnelling Society, the Federal Route Office of Nidwald and NAGRA.

Hauenstein Base tunnel

During construction of Hauenstein Base railway tunnel vertical displacements up to 1000 mm were measured in the zone excavated through the Gipskeuper; however, no important movements were observed in the zone of Opalinus claystone (see figure 24). Opalinus is an overconsolidated medium-activity claystone in with mixed layer clays and illite are the main components of the fine fraction. High quartz content (30%) is usually reported in this material (Einstein, 2000). Opalinus claystone is known to be an expansive clay rock if it is initially unsaturated and it is subjected to water saturation. Information on the hydrogeological regime in the rock massif of Hauenstein Base tunnel is, unfortunately, unknown.

Figure 23. Location of main tunnels excavated in sulphate-bearing rocks in Jura Mountains (after Madsen et al., 1995).

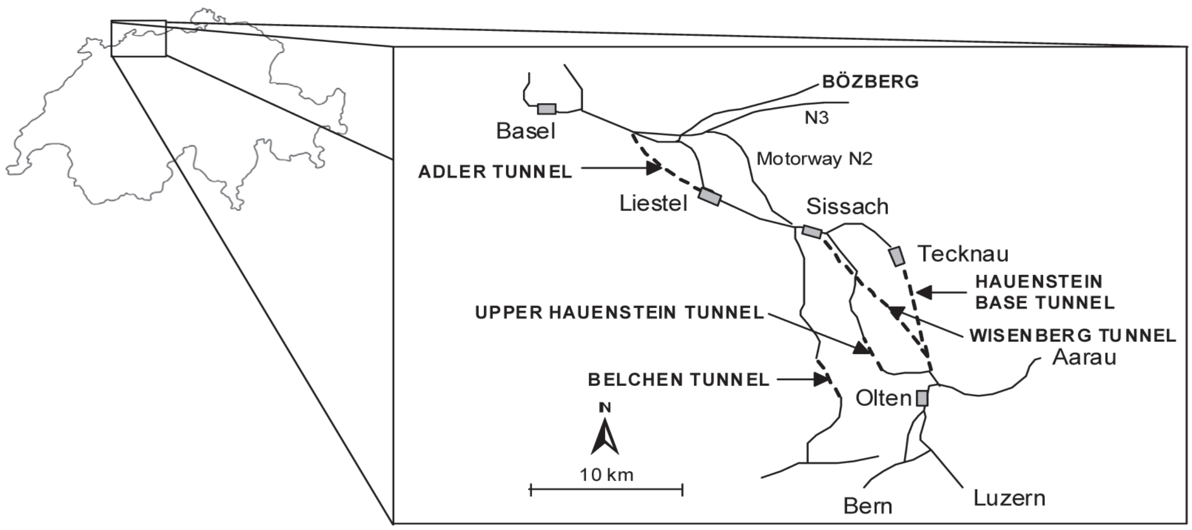
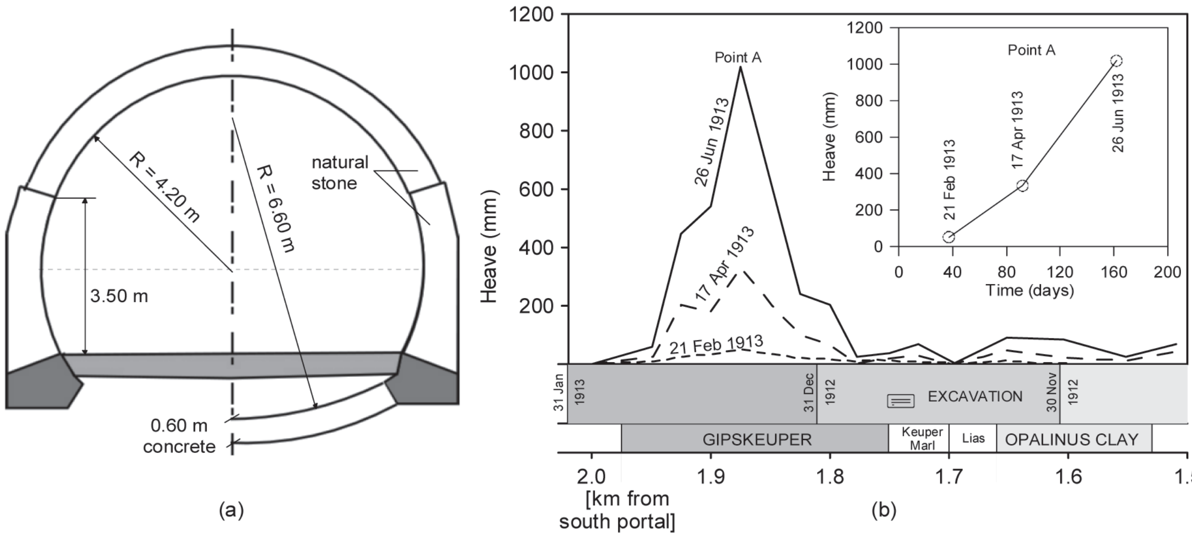


Figure 24. (a) Standard cross-section in Hauenstein Base tunnel. (b) Floor heave during construction (original Figures by Wiesman, 1917; modified after Amstad and Kovári, 2001).



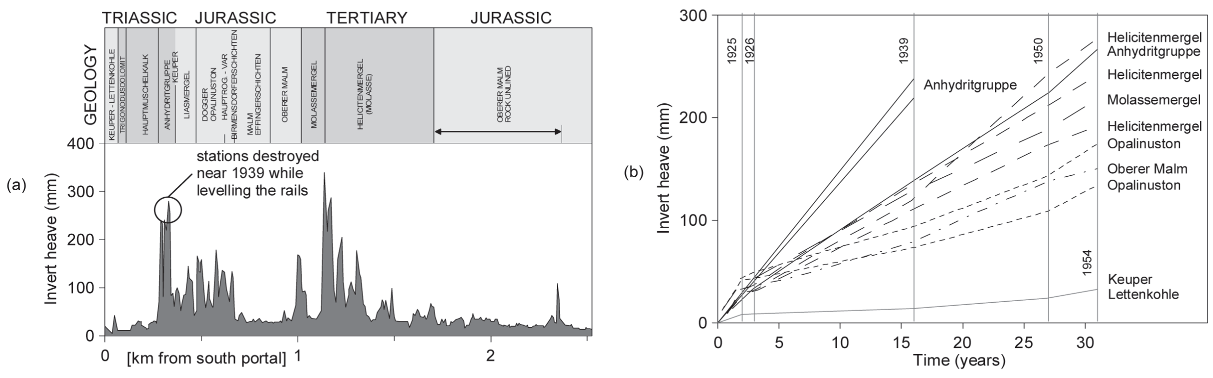
Only one year after tunnel opening, damage became evident in several sections in the tunnel lining due to swelling, leading to initial refurbishments between 1919 and 1923. During operation until the end of the 70's, swelling in the Gipskeuper led to heave in the tunnel floor averaging 1 cm/year, particularly in sections with flat-slab (Kovári & Descoeudres, 2001).

Bözberg railway tunnel

The Bözberg tunnel was constructed between 1871 and 1875. It has a length of 2.5 km and crosses a series of expansive materials varying from the Triassic to the Tertiary ages, as illustrated in figure 25a. This figure clearly shows the dependence of swelling phenomena on the type of rock. As in Hauenstein tunnel, in Bözberg information on the hydrogeological regime in the rock massif is unknown.

Abutments in some sections were reconstructed several times and invert-arches were built between 1903 and 1905. Einstein (1979) indicates that the concrete of inverts were rapidly destroyed by the attack of highly sulphated water and that these failures were associated with the destruction of the drainage channel. Measurements taken during a period of 31 years since 1923 showed a maximum heave rate of 14 mm/year in the Gipskeuper. The increase of displacements was practically linear with time (figure 25b). Between 1963 and 1967 new invert-arches were constructed in zones affected by the strongest vertical displacements.

Figure 25. (a) Geological longitudinal section of the Bözberg railway tunnel. (b) Evolution of heave in materials involved in tunnelling (Grob, 1976).



Belchen tunnel

Expansive phenomena during construction of the two tubes of Belchen tunnel were analyzed in detail by Prof. Grob and co-workers at ETH in the early 70's and by Einstein (1979) at MIT. Excavation involved mainly the Gipskeuper and the Opalinus Claystone, as illustrated in the longitudinal geological profile of the tunnel presented in figure 26. The two tubes of Belchen were constructed according to the principle of resisting support by excavating the invert drifts and then enlarging them to the full cross section.

Just after the excavation swelling phenomena caused the failure of inverts. Figure 27 illustrates the heave measured during construction (1963-1967) in both the drainage pipe and the floor (Grob, 1972, 1976), as well as the conditions of both structures as a result of the swelling. After its failure, the invert (or countervault, as it is called by Grob, 1972) raised 120 mm within 8 days and 400 mm within months (Kovari and Descoeudres, 2001). The drainage pipe exhibited also significant swelling in Opalinus claystone and other formations.

Swelling in clayey materials often presents a maximum value after saturation and this could be an interpretation of the phenomenon observed in the zone of Belchen excavated in Opalinus claystone after invert construction. The maximum swelling was generated during hydration of the clay as a result of leakage from the drainage pipe. After construction of the invert on a deformed foundation material additional swelling was supported by the rigid base.

Figure 26. Geological longitudinal section of Belchen tunnel (Kanton Basel-Landschaft info-site).

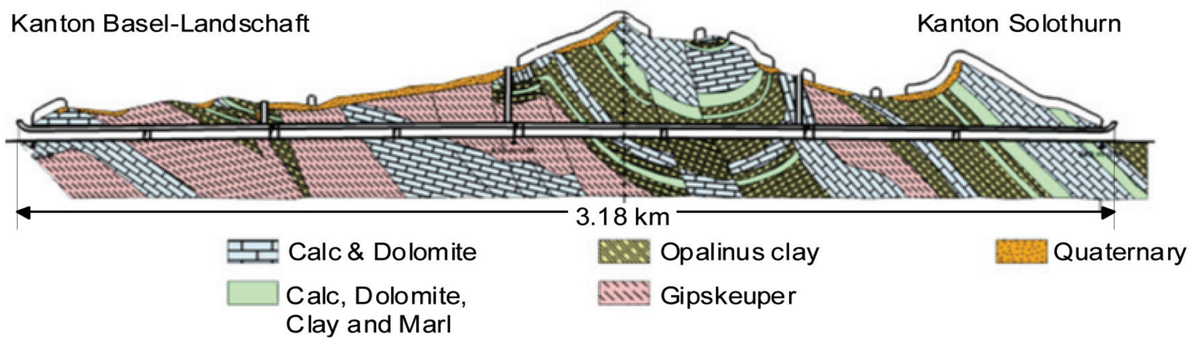
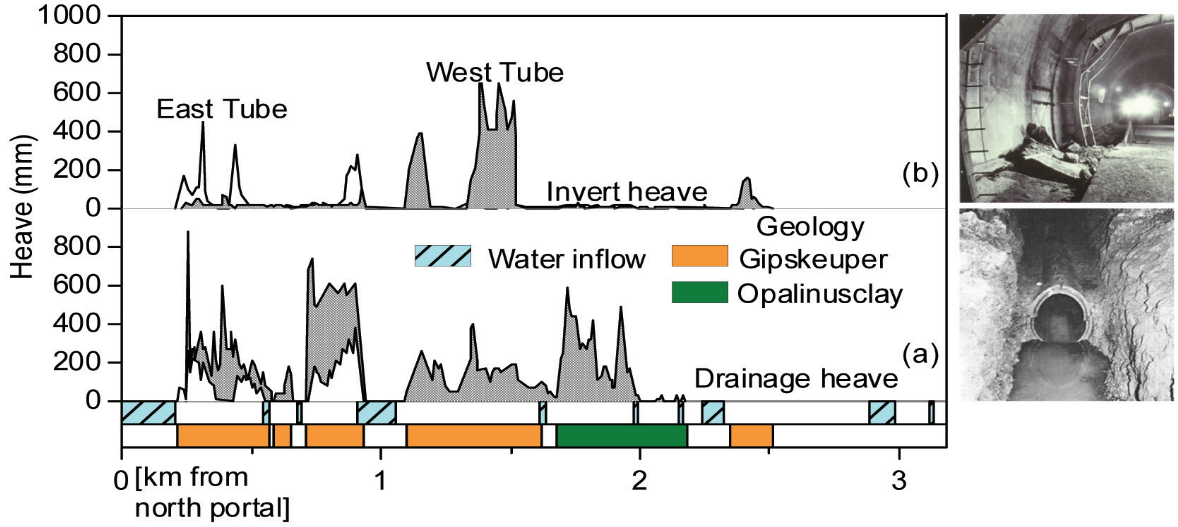


Figure 27. Belchen tunnel (1963-1970): (a) heave and failure of the drainage pipe before construction of the invert, (b) heave and failure of the original invert during construction (original Figures by Grob, 1972, 1976; modified after Amstad and Kovári, 2001).



A new invert-arch with a radius of R = 10.4 m and a thickness of t = 0.45 m was constructed after the first expansive phenomena were detected; however, it was sheared off shortly after construction and a further 600 mm of invert heave occurred. This required the construction of another cross-section with an invert-arch having a radius of 8.12 m and a thickness of 0.85 m (Einstein, 1979) (see figure 28). Instrumented sections were equipped with load cells between the invert and the rock, as well as within the concrete. These data —reported by Huder and Amberg (1970) and Grob (1972)—, are presented in figure 29. The difference between the pressures measured in Gipskeuper and Opalinus claystone is close to one order of magnitude.

An extensive study of the heave affecting Belchen tunnel began in 1986 to check the conditions of the foundation material eighteen years after construction (Kovári & Amstad, 1993). Unfortunately, swelling pressure was not measured during the monitoring program. The result of observations by means of sliding micrometers revealed that swelling was active in some sections in the Gipskeuper almost until 1995 —just six years before the latest repair works, initiated in 2001 and finished in 2003— (figure 30).

Figure 28. Standard resisting support cross-section with 0.45 and 0.85 m thick inverts in Belchen tunnel

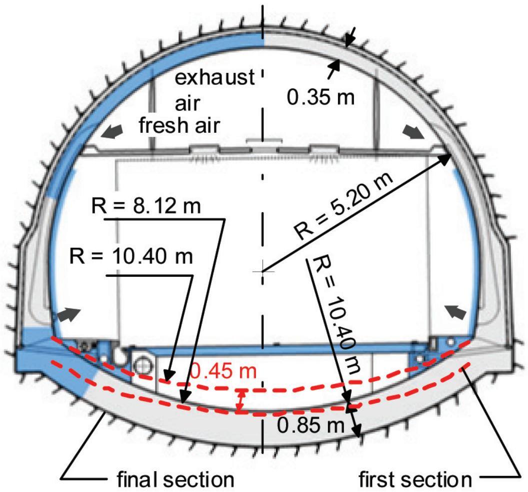


Figure 29. Total radial pressure in the reinforced invert-arch of Belchen tunnel (t = 0.85 m)

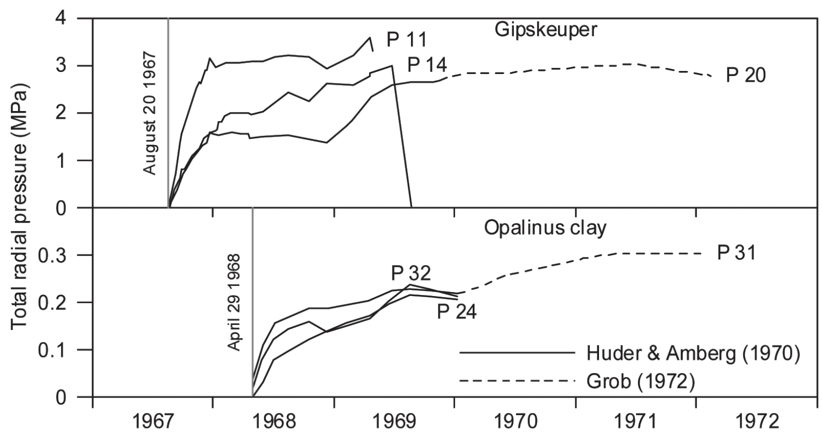
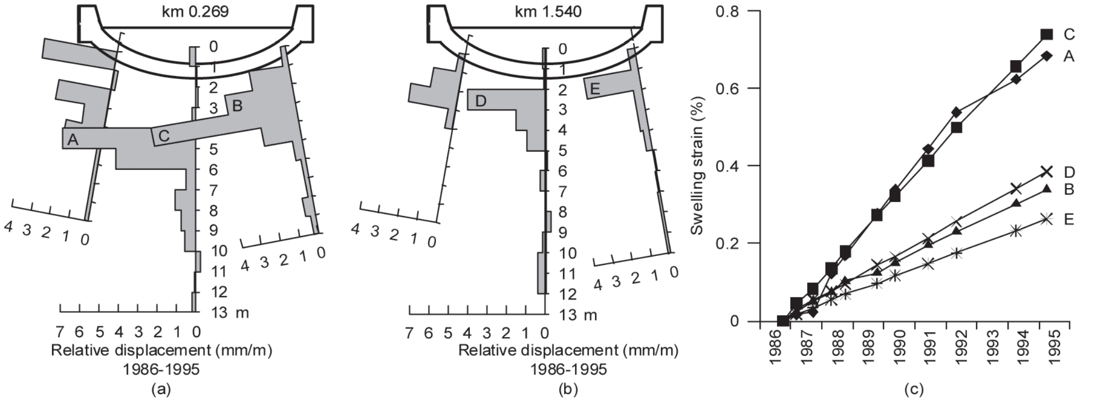


Figure 30. Extensometer measurements in two sections of Belchen tunnel located in the Gipskeuper (modified after Amstad & Kovári, 2001). (a) and (b) show the strains within the rock measured in chainages 0.269 and 1.540 km, (c) shows the development of swelling strains in time at some particular locations in (a) and (b).



Damage affecting Belchen tunnel during operation were unequivocally related with the interaction between sulphate-rich water and the atmosphere into the tunnel. Werder (1989) pointed out that sulphate content in groundwater from the Belchen rock massif is 1290 ppm. In this sense, the role played by construction joints and other unsealed fissures was the determining factor in crystallization of gypsum into these structural discontinuities. This hypothesis is confirmed by observations in the tunnel just before the latest repair works, as illustrated in figure 31. The same phenomena were detected during construction of Bözberg road tunnel, as pointed out by Kovári & Descoeudres (2001). Very high sulphate and chloride rich water was detected in some deposits and crystal growth caused local instabilities in segmental rings of the lining (see figure 32). The origin of this water was associated with a very old deep-lying groundwater capable of generating a flow of about 10 L/min.

Figure 31. Damage of Belchen tunnel during operation between 1970 and 2001. (a) Type of damages affecting the standard cross-section. (b) Crystal growth in fissures caused by vault cracking and abutment spalling (images from Bundesamt für Strassen - Switzerland).

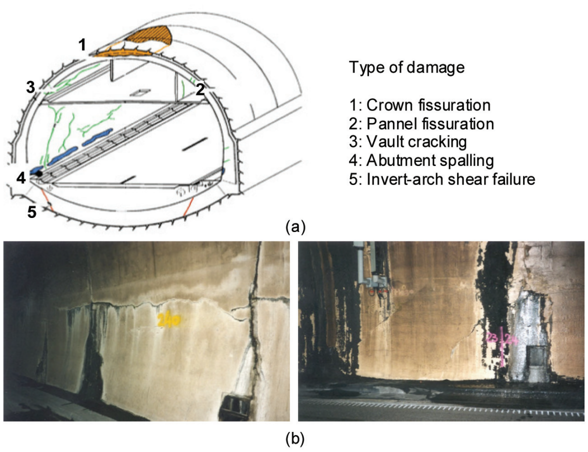
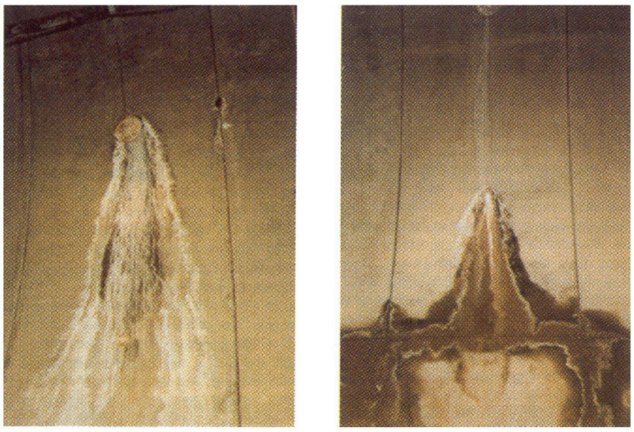


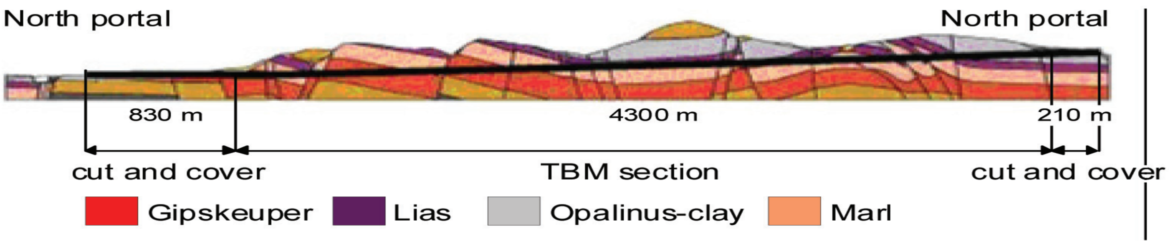
Figure 32. Crystallization of sodium sulphate and calcium chloride between segmental rings in Bözberg road tunnel (Kovári & Descoeudres, 2001).



Adler tunnel

The 5340 m long Adler tunnel forms part of “Railway 2000 Project” and bypasses the present lines between Basel and Liestal. The occurrence of expansive rocks in the tunnel has been studied in detail by Hauber et al. (2000), Meyer (2001) and Noher et al. (2006), and is summarized as follows. In the central part the Opalinus claystone —with mixed-layer clayey minerals (illite/smectite)—, occur in the overburden and the north portal is located completely in this rock. 1095 m of the central part are located in the Gipskeuper (see figure 33).

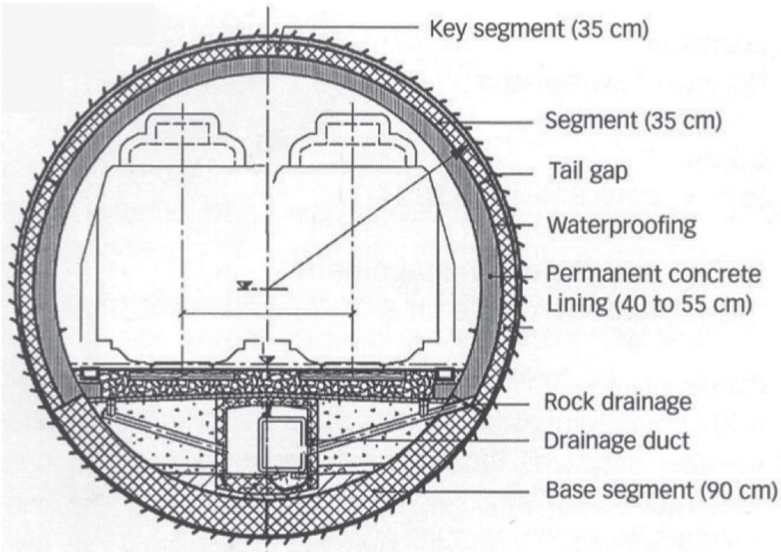
Figure 33. Geological longitudinal section of the Adler tunnel and construction methods used during excavation (Hauber et al., 2000).



Adler was designed in according to the principle of resisting support with a diameter of 12.58 m. To withstand the swelling pressures in clay rocks as well as in the Gipskeuper two standard circular cross sections were defined (Noher et al., 2006). For clay rocks a maximum swelling pressure of 1.2 MPa was taken into account and for the Gipskeuper the maximum swelling pressure was assumed to be 6 MPa. These values were obtained from laboratory tests following the Suggested Methods for Laboratory Testing proposed by the ISRM (1989).

The tunnel was excavated by a TBM in shield and lined with precast elements. This method certainly reduces damage caused by excavation; however, in order to prevent swelling during construction some technical actions were specified (Kovári & Descoeudres, 2001): (i) immediate injections of mortar in the annular gap behind the dowels, (ii) a short ring closure time of three months maximum between excavation and the complete bearing ring, (iii) removal of groundwater at the cutterhead. The same authors point out that a waterproof seal was laid on the dowel ring in the traffic zone, before the installation of the in situ concrete secondary lining, but the invert was not sealed. References to the groundwater composition are only related to their corrosive effect on concrete.

Figure 34. Standard cross-section for the driven tunnel section (TBM section) (Kovári & Descoeudres, 2001).



For the tunnel section in the Gipskeuper dowels with a thickness of 0.9 m were used at the floor. The dowels at the side walls and the roof have a thickness of 0.45 m. In this area 0.45 m cast-in-place concrete completes the internal lining. Therefore the thickness of the lining in the Gipskeuper zone is 0.9 m throughout (see figure 34).

A monitoring program in four sections located in the zone of the Gipskeuper (tm 1313, tm 1430, tm 1958 and tm 2100) was initiated in 1999. Observations consist in deformation monitoring at the dowels, measurement of deformation and inclination in drillings (toe of drillings is 30 m distant to the tunnel), measurement of the state of stresses approximately 1 m beneath the tunnel floor and the swelling pressure acting on the floor dowels, both using pressure cells (Noher et al., 2006) (see figure 35). Data on pressures and stresses reported by Noher et al. (2006) are presented in figure 36.

A clear tendency to swelling stabilization is observed in this case and the pressure measured by 15 of the 16 sensors is equal or less than 1.8 MPa. However, Noher et al. (2006) pointed out that one sensor in the section MQ 1313 showed a pressure of about 4 MPa in 2003. 1 m below the tunnel a different behaviour has been detected: stresses up to 3.8 MPa have been measured in the longitudinal direction indicating the possibility of stress rotation after swelling in the active zone. The middle and lower sensors show low values, less than 0.5 MPa, and a decrease since 2003.

Figure 35. Monitoring sections in the Gipskeuper of Adler tunnel (Noher et al., 2006). GMI: positions of inclinometer and sliding micrometers, PB: swelling pressure monitoring system, S: ground stress monitoring station.

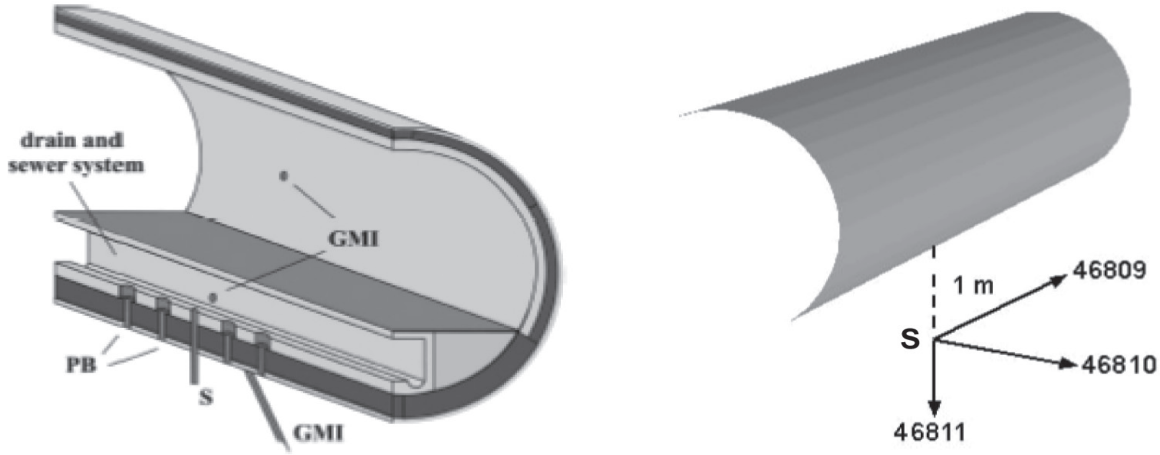
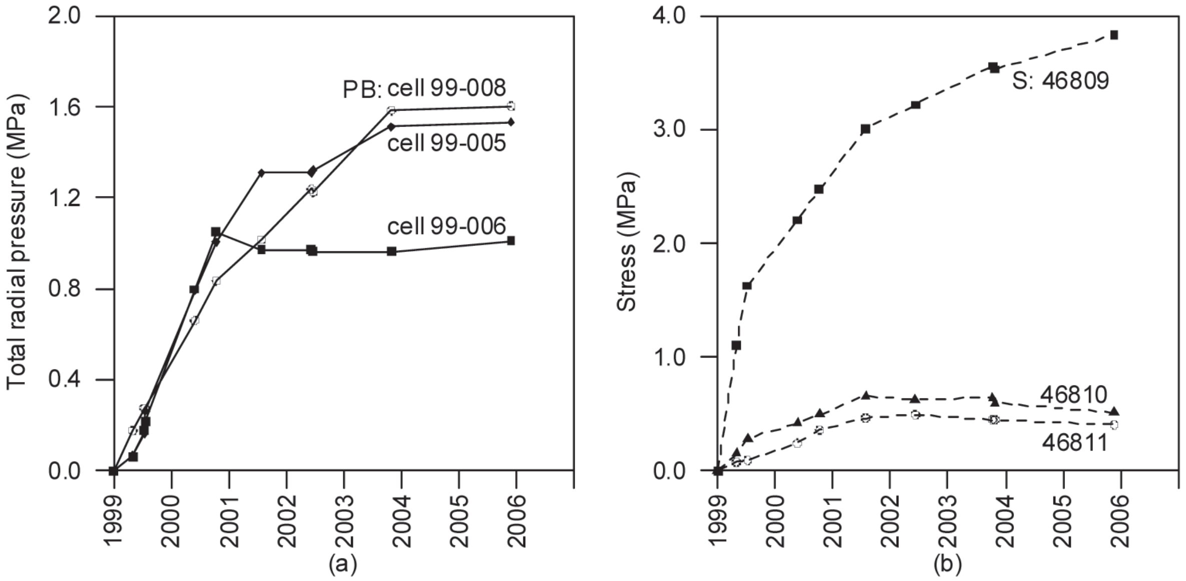


Figure 36. Pressure monitoring in the Gipskeuper in Adler tunnel: (a) pressure evolution at the lining in section MQ 1430, (b) pressure evolution 1 m below the invert in section MQ 1313 (after Noher et al., 2006).



Conclusions

Main general aspects regarding swelling in tunnels excavated through Triassic SBR can be summarized as follow:

i. Expansive phenomena in SBR far exceed the expansivity threshold of most rocks and hard soils, which are well-known because of their high expansive potential (i.e. Molasse marl, Opalinus clay, Tabuk clay, Al-Qatif clay and other similar). In tunnels excavated through alternations of clayey-marly swelling rocks and SBR (i.e. Hauenstein, Bözberg and Belchen), it became clear that under similar conditions during construction and operation —particularly, under the same ventilation conditions (relative humidity, temperature and wind velocity) both heave and swelling pressure in SBR could be up to one order in magnitude greater than in expansive clayey and marly rocks.

ii. Long term observations in tunnels reveal that expansive phenomena affect exclusively the floor. Abutments and vaults remain unaffected even under strong swelling of the foundation material. This feature is unequivocally related to preferential water flow toward the bottom of excavations, where it is able to wet the material initially affected by the stress relief or evaporate due to ventilation. Then, expansion in tunnels occur preferentially in zones of water accumulation and rock weathering and not precisely in zones exposed only to water flow.

iii. Swelling is characterized by a sudden activation immediately after excavation, just when the rock undergone extreme changes in both confinement and suction due to the stress relief and is exposed to the environmental agents. This hypothesis is validated by the important expansive response observed after reconstruction works in the south tunnel of Wagenburg, a task that undoubtedly caused unloading and new changes in suction in the foundation material.

iv. Heterogeneous distribution of swelling —particularly the distribution of swelling pressure, even in cases of homogeneous layers of SBR—, is a consequence of intrinsic heterogeneity these rocks, as well as the result of an erratic configuration of the active zone.

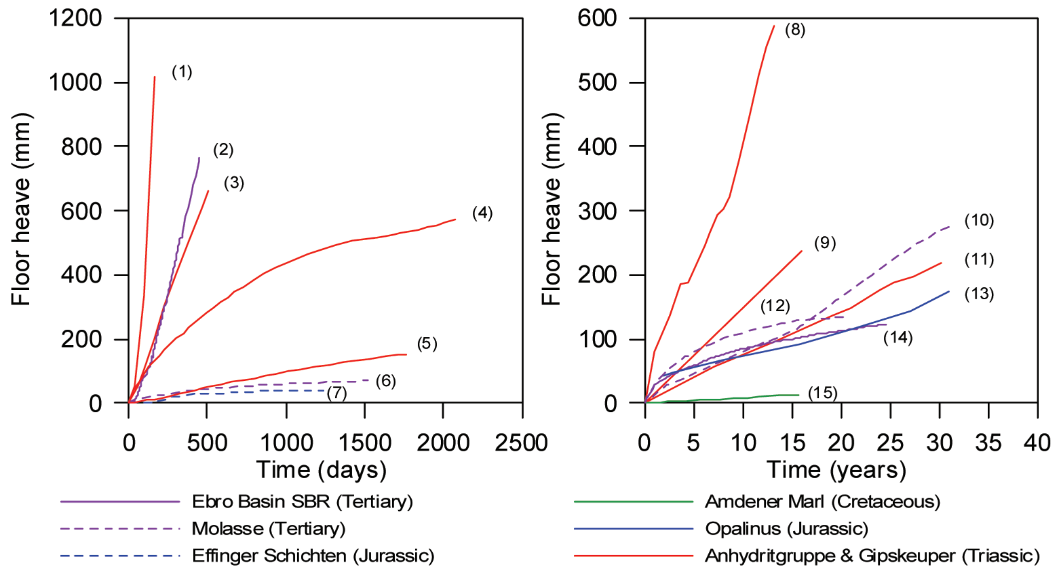
v. The active zone seems to be not affected significantly by the shape of excavation and remained relatively constant since the beginning of expansive phenomena. Consequently, it is reasonable to assume that the weathering of the foundation material in tunnels excavated in SBR is also limited to a relatively well defined thickness.

vi. After activation —and depending on support rigidity—, either heave or swelling pressures in SBR evolve at very high rates and, in some cases, an ultimate value can not be clearly defined; in contrast to some clayey rocks, characterized by asymptotic swelling-time relationships (see figures 37 and 38).

vii. Evidences of a cause-effect relationship between self-sealing mechanisms and attenuation of either heave or swelling pressure in tunnels with resisting support are not available.

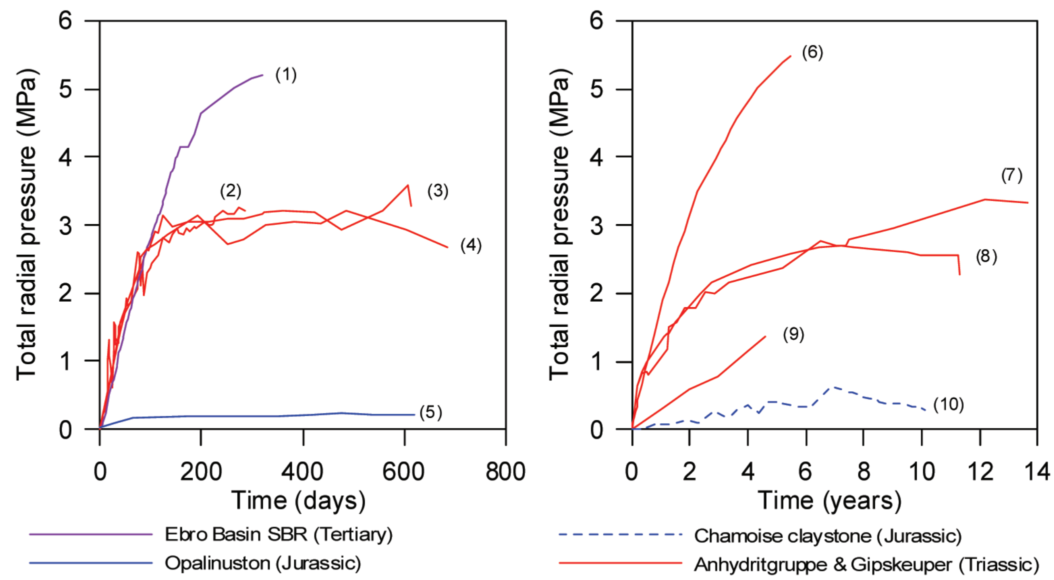
viii. Even when important quantities of active clayey minerals are present in the host matrix of SBR (i. e. Corrensite in the Gipskeuper) —but principally in spite of the well knowledge on the asymptotic expansive behaviour of pure clayey materials—, at field scale it is difficult distinguish between the contribution of the clay expansion and the expansion due to the transformation of anhydrite into gypsum; if the latter is really possible. Then, the validity of this classic approach to interpret field swelling-time relationships in SBR is open to discussion.

Figure 37. Floor heave-time relationships in tunnels excavated through swelling rocks



(1) Hauenstein Base (Amstad & Kovári, 2001), (2) Lilla 411+880 (Alonso et al, 2004), (3) Wagenburg ST E 360 (Krause & Wurm, 1975), (4) Wagenburg TT II E 3 - wet (Nagel, 1986), (5) Freudenstein TG Block XIV (Fecker, 1992), (6) and (12) Luftschutzanlage Leonhardsplatz (Amstad & Kovári, 2001), (7) T8 Biel-Sonceboz (Amstad & Kovári, 2001), (8) Wagenburg NT E 391 (Nagel, 1986), (9), (10) and (13) Bözberg (Grob, 1976) (11) Wagenburg ST E 387 (Paul & Wichter (1996), (14) Ascó II NPS (Berdugo, 2006), (15) Seelisberg (Amstad & Kovári, 2001)

Figure 38. Swelling pressure-time relationships in tunnels excavated through swelling rocks



(1) Lilla 411+829 (Alonso et al, 2004), (2) Heslach II (Kiehl & Wittke, 1991), (3) Belchen (Huder & Amberg, 1970), (4) Wagenburg TT II - wet (Wichter, 1985), (5) Belchen (Huder & Amberg, 1970), (6) Wagenburg ST E 409 (Paul & Wichter, 1996), (7) Wagenburg TT I - dry (Wichter, 1985), (8) Wagenburg TT II - wet (Wichter, 1985), (9) Freudenstein TG Block VIII (Fecker, 1992), (10) Chamoise (Leger, 1999).

Acknowledgements

The Ministry of Public Works of Spain was the financial supporter for this study. The authors wish to thank the support provided by their colleagues Prof. Dr. Ing. Marcos Arroyo-Álvarez de Toledo and Prof. Dr. Ing. Maarten Saaltink.

Bibliography

Abduljauwad, S.N., Al-Sulaimani, G.J., Basunbul, I.A. & Al-Buraim, I.A. (1998). Laboratory and field studies of response of structures to heave of expansive clay. Géotechnique 48, No. 1: 103-121.

Amstad, C. &. Kovári, K. (2001). Untertagbau in quellfähigem fels. Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation (UVEK) & Bundesamt für Strassen (ASTRA), Zürich.

Berdugo, I.R., Alonso, E.E. & Romero, E.E. (2006). Swelling mechanisms in sulphate-bearing rocks. Proc. Eurock 2006, Van Cotthen, Charlier, Thimus & Tshibangu eds, Taylor & Francis Grup, London: 451-454.

Berdugo, I.R. Alonso, E.E. , E. Romero y A. Gens. Tunnelling And Swelling In Triassic Sulphate-Bearing Rocks. Part I - Case studies from Baden-Württemberg. Revista Epsilon, No. 12, pp., 1-17.

Berner D. (1991). Die Geologie des Freudensteintunnels, Ingenieurbauwerke, DB Neubaustrecke Mannheim-Stuttgart, Nr. 7.

Bischoff, N., Hagmann, (1977). Field instrumentation for the design of tunnels in swelling rock. Int. Symp. für Untertagbau, Luzern: 657-668.

Dhowian, A.M. (1984). Characteristics of expansive clay-shale in the northern region of Saudi Arabia. 5th International Conference on Expansive Soils, Adelaida: 316-320.

Einstein, H. (1979). Tunneling in Swelling Rock. Underground Space. Vol. 4, No. 1: 51-61.

Einstein, H. (2000).Tunnels in Opalinus Clayshale - a review of case histories and new developments. Tunnelling and Underground Space Technology, v. 15, n. 1: 13-29.

Fecker, E. (1992). Untersuchung von schwellvorgängen und erprobung von auskleidungskonzepten beim Freudensteintunnel. Tunnelbau 1996, Deutsche Gesellschaft für Geotechnik e.V., Verlag Glückauf GmbH, Essen: 16-20.

Götz, H.P. (1972). Zur frage der sohlhebungen im Gipskeuper. Int. Symp. für Untertagbau, Luzern: 128-132.

Grob, H. (1972). Schwelldruck im Belchentunnel. Int. Symp. für Untertagbau, Luzern: 99-119.

Grob, H. (1976). Swelling and heave in Swiss tunnels. Bulletin - Association of Engineering Geologists, 13: 55-60.

Hauber, L. (1996). Die Geologie des Adlertunnels. Schweizer Ingenieur und Architekt, Nr. 18: 341-344.

Hauber, L., Noher, H.P., Meyer, M. & Horal, G. (2000). Geologie im bereich Adlertunnel. Tec 21, Nr. 49/50: 9-12.

Henke, K.F. (1976). Magnitude and rate of heave in tunnels in calcium sulphate bearing rocks. Bulletin - Association of Engineering Geologists, 13: 61-64.

Huder, J. & Amberg, G. (1970). Quellung in Mergel, Opalinuston und Anhydrit. Schweizerische Bauzeitung, Jhrg. 88, 43.

ISRM (1999). Suggested Methods for Laboratory Testing of Swelling Rock. Int. J. Rock. Mech. Min. Sci. 36: 291-306.

Kaiser, W. (1976). Behaviour of anhydrite after addition of water. Bulletin - Association of Engineering Geologists, 13: 68-69.

Khemakhem, M.,Ben Jdidia, M., Bouarada, Z. (2002). Identification des paramètres de gonflement d'un sol de Bir Ali Ben Khalifa (Tunisie). Paramètres de calcul géotechnique, Magnan (ed): 133-144.

Kirschke, D. (1987). Laboratory and in situ swelling test for the Freudenstein tunnel. Proc. 6th ICRM, Montreal, v. 3: 1492-1496.

Kirschke, D., Kovari, K. & Prommersberger, G. (1991). Bemessungsgrundlagen und Konstruktion der Sohle des Freudensteintunnels. Ingenieurbauwerke, DB Neubaustrecke Mannheim-Stuttgart, Nr. 7.

Kovári, K., Amstad, C. & Anagnostou, G. (1988). Tunnelling in swelling rocks. Proc. 29th U.S. Symp. Rock Mech. Balkema, Cundall et al. (eds.): 17-32.

Kovári, K. & Amstad, C. (1993). Decision making in tunnelling based on field measurements. In Comprehensive rock engineering: principles, practice & projects, Oxford-Pergamon Press: 571-606.

Kovári, K. & Descoeudres, F. (2001). Tunnelling Switzerland. Swiss Tunnelling Society.

Krause, H. (1976). Sulphate rocks in Baden-Württemberg and their importance in relation to civil engineering. Bulletin - Association of Engineering Geologists, No.13: 45-49.

Krause, H. (1977). Zur geologie und statistik des tunnelbaus in Baden-Württemberg unter besonderer berücksichtigung der Keupertunnel, Jh. geol. Landesamt, Baden-Württemberg.

Krause H., Wurm F. (1975). Geologische Grundlagen und Untersuchungen zum Problem der Sohlhebungen in Keupertunneln Baden-Württembergs, Strassenbau und Strassenverkehrstechnik, Heft 184.

Kurz, G. & Spang, J. (1984). Instandsetzung und Erneuerung der Blähstrecke des Kappelesbergtunnels, Bautechnik, Heft 11: 365-376.

Lippmann, F. (1976). Corrensite, a swelling mineral, and its influence on floor heave in tunnels in the Keuper formation. Bulletin - Association of Engineering Geologists, No.13: 65-68.

Lombardi, G. (1979). Rock Mechanics at the CERN Proton-Antiproton Facilities, 4th. Int. Congress on Rock Mechanics, Montreux, Vol. 3: 433-436.

Madsen ,F. & Nüesch, R. (1990). Langzeitverhalten von Tongesteinen und tonigen Sulfatgesteinen, Mitteil. des Inst. für Grundbau und Bodenmechanik Nr. 140, ETH, Zürich.

Madsen, F., Flückiger, A., Hauber, L., Jordan, P.& Vögtli, B. (1995). New investigations on swelling rocks in the Belchentunnel, Switzerland, Proc 8 Int Congr Rock Mech, v. 1: 263-267.

Meyer, M. (2001). Die Geologie des Adlertunnels. Bull. angew. Geol, Vol. 6, Nr. 2:199-208.

Nagel, D. (1986). Sohlhebungen in den Keupertunneln von Baden-Württemberg, Tunnelbau, Kontakt & Studium, Band 184: 110-125.

Noher, H.P., Vögtli, B. & Kister, B. (2006). Swelling —a geotechnical problem at the Adler Tunnel, Switzerland— monitoring results and their interpretation. Proc Eurock 2006, Van Cotthen, Charlier, Thimus & Tshibangu eds, Taylor & Francis Grup, London: 337-342.

Paul, A. & Wichter, L. (1996). Das langzeitverhalten von tunnelbauwerken im quellenden gebirge - neuere messergebnisse vom Stuttgarter Wagenburgtunnel, Taschenbuch für den Tunnelbau, Verlag Glückauf, Essen: 1-15.

Paul, A. & Walter, F. (2004). Measurement of stress changes in rock and rock mass and structures with pressure cells. Bautechnik 81: 639-647.

Prommersberger, G. & Kuhnhenn, K. (1989). The Freudenstein tunnel: tunnel construction in swelling rocks. Proc. Rapid Excavation and Tunneling Conference: 678-700.

Sahores, J. (1962). Contribution à l'étude des phénomenes mécaniques accompagnant l'hydratation de l'anhydrite. Revue des materiaux de construction.

Solexperts (2006). HDC® in Chienberg tunnel (Jura Mountains).

Spaun, G. (1974). Über die Ursachen von Sohlhebungen in Tunneln des Gipskeupers, Festschrift Leopold Müller, Karlsruhe.

Steiner, W. (1993). Swelling rock in tunnels: rock characterization, effect of horizontal stresses and construction procedures. Int. J. Rock Mech. Min. Sci. & Geomech. Abstrs, vol. 30, no. 4: 361-380.

Thut, A., Naterop, D., Steiner, P. & Stolz, M. (2007). Tunnelling in Squeezing Rock-Yielding Elements and Face Control. Solexperts document: 8 p.

Werder, F. (1989). Sanierungs- und erneuerungsarbeiten im Belchentunnel (N2), Dokumentation D 037 des Schweiz. Ingenieur- und Architektenvereins.

Wiesman, E. (1917). Der Bau des Hauenstein-Basistunnels, Denkschrift.

Wichter, L. (1985). Results of long-term measurement in the Wagenburg túnel in Stuttgart. Tunnel, Vol. 4: 254-257.

Wichter, L. (1991). Horizontal stresses in anhydriceous Rock. Proc. Int. Congr. Rock Mech. Aachen, S: 367-370.

Wittke, W. (1990). Rock mechanics: theory and applications with case histories. Springer-Verlag, Berlin.

Wittke, W. & Rißler, P. (1976). Bemessung der Auskleidung von Hohlräumen in quellendem Gebirge nach der Finite Element Methode. Veröffentlichung des Inst. für Grundbau, Bodenmechanik, Felsmechanik und Verkehrswasserbau der RWTH Aachen, Heft 2.

Wittke, W. & Pierau, B. (1979). Fundamentals for the design and construction of tunnels in swelling rocks. Proc. Int. Congr. on Rock Mechanics, Montreux, Vol. 2: 719-729.

Wittke-Gattermann, P (1998). Bemessung von Tunneln in quellendem Gebirge. Forum für junge Geotechnik-Ingenieure, 25. Baugrundtagung, Stuttgart.

Wittke-Gattermann, P. (1998). Verfahren zur Berechnung von Tunnels in quellfähigem Gebirge und Kalibrierung an einem Versuchsbauwerk. Geotechnical engineering in research and practice, WBIPRINT. 1. Essen: Glückauf.

Wittke, W. (2000). Stability analysis for tunnels. Verlag Glückauf GmbH, Essen.

Wittke-Gattermann, P. & Wittke, M. (2004). Computation of strains and pressures for tunnels in swelling rocks. Tunnelling and Underground Space Technology 19: 422-423.

Wittke, W & Wittke, M. (2005). Design, construction and supervision of tunnels in swelling rocks. Underground space use: Analysis of the past and lessons for the future, Taylor & Francis Group, London, Erdem & Solak (eds): 1173-1178.

Wittke, M. (2006). Design, construction, supervision and long-term behaviour of tunnels in swelling rocks. Proc Eurock 2006, Van Cotthen, Charlier, Thimus & Tshibangu eds, Taylor & Francis Grup, London: 211-216.

Young, R.G. (2004). Swelling of Sunshine clay and stability of roads. RFT Report A21: 214-219.