Swelling of a gypsiferous claystone and its modelling

Gonflement d'une argilite gypsifère et sa modélisation

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ABSTRACT

Excavations in anhydritic-gypsiferous claystones may experience severe swelling phenomena. The intensity of the expansive behaviour observed in these materials is higher than the expansion developed in other expansive sulphate-free rocks and soils. Tunnel functionality and stability is impaired in most cases. Field observations in Lilla tunnel as well as laboratory tests results have demonstrated that the swelling process is associated with gypsum crystal growth in discontinuities. Crystal growth is a consequence of groundwater supersaturation in sulphate content. The purpose of the work described in the paper is to develop a calculation model, suitable for predicting expansions at the excavation design stage.

RÉSUMÉ

Les excavations dans des argilites anhydritiques-gypsifères peuvent expérimenter des problèmes importants de gonflement. L'intensité du comportement gonflant observée dans ces matériaux est plus haute que celle développée dans d'autres roches et sols gonflants ne contenant pas de sulfates. La fonctionnalité et stabilité des tunnels sont altérés dans la plupart des cas. Les observations in-situ du tunnel de l'Illa et les résultats de laboratoire ont démontré que le procès de gonflement est associé à la croissance du cristal de gypse dans les disconcontinuités. La croissance du cristal est une conséquence de la supersaturation en eau souterraine en contenu de sulfate. L'objectife du travail que décrit cet article est de développer un modèle de calcul adéquat pour prédire les gonflements dans la phase de conception de l'excavation.

Keywords : Tunnel, swelling, gypsum, anhydrite, claystone, crystallization, evaporation

1 INTRODUCTION

The case of Lilla tunnel, a high speed railway tunnel in Spain whose invert underwent severe damage during construction (2002-2003), is described in some detail in Alonso et al. (2007) and Berdugo et al. (2006). Lilla tunnel was excavated in the Ebro Basin East limit, near Montblanc (Catalunya). Its length was 2 km, with a maximum gradient of 2.5%. Overburden varies from 32 to 120 meters. It was originally excavated with a horseshoe shaped cross-section. The excavated mean vault radius was 6.75 m. The excavation was performed by drill and blast from the two portals, dividing the section into head and bench. The characteristics of the original lining and flat slab are described in Figure 1. The floor of the tunnel was exposed to the action of environmental agents for most of the construction period, since the flat-slab was only concreted after the total excavation of the bench. Waterproofing of the excavated section was restricted to portals due to the low permeability of the massif.

Large expansive phenomena occurred in a generalized way at floor level. First expansions were detected in the flat-slab in September 2002, just after the flat-slab of its original section was concreted. The heave was measured during more than a year. In the most critical section a maximum of 800 mm was registered. Extreme swelling pressures up to 5 MPa were measured on the rock-concrete contact in a test section having an invert arch (Figure 2).

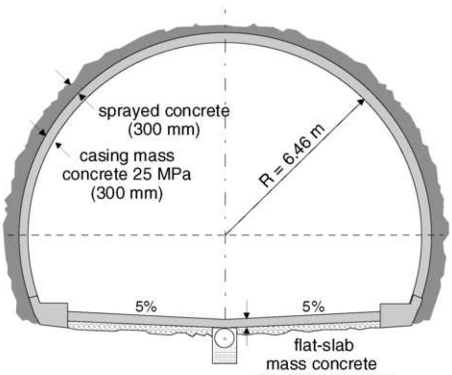

Figure 1. Original cross-section in Lilla tunnel.

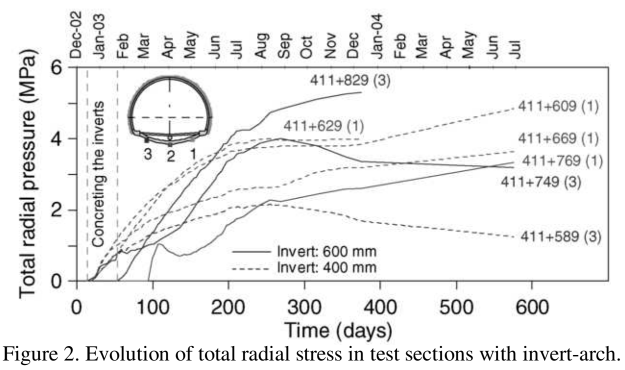

Figure 2. Evolution of total radial stress in test sections with invert-arch.

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2 SWELLING PHENOMENA

The expansive phenomena observed motivated some "in situ" and laboratory experimental work. Test sections with flat-slab and invert-arch were constructed and instrumented. An "in situ" flooding test with groundwater was performed in some instrumented circular test sections. Vertical strain profiles and radial pressures in the foundation material and in the vault were obtained by means of sliding micrometers and pressure cells, respectively. Continuous undisturbed core specimens of the foundation material were recovered, and a set of laboratory tests was performed in order to obtain quasi-continuous profiles of geotechnical properties of the samples, including the mineralogical composition of the rock.

2.1 *Field evidence of crystal growth*

The subsoil investigation program carried out defined that the excavated material has two main components, a clay matrix constituted by illite and palygorskite, and a crystalline fraction made up of anhydrite and gypsum. It was found that groundwater had a high sulphate content and an active zone was identified in the foundation material where the expansive phenomena (swelling strains) occurs. The limit of the active zone was not deeper than 4 to 5 meters below the floor level of the tunnel.

In all studied rock profiles the active zone was characterized by the occurrence of neo-formation gypsum needles on relic slickensided surfaces opened by the stress relief caused during tunnel excavation (Figure 3a). A description of the mineralogical composition of the rock is presented in Figure 4 which shows the variation in anhydrite and gypsum content in the active zone. This information was obtained from laboratory tests on undisturbed samples.

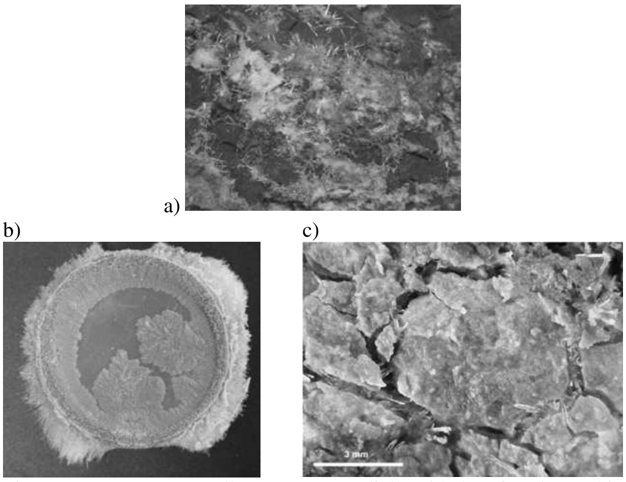

Figure 3. a) Gypsum needles on an open slickensided surface located in the active zone. b) Gypsum crystal growth on the surface of a powdered compacted sample, bottom face (Berdugo 2007). c) Evidences of degradation due to crystal growth on a sample at the end of a drying test (Oldecop 2006).

2.2 *Laboratory evidence of crystal growth*

Some tests performed in laboratory have shown evidences of crystal growth. Gypsum crystal growth occurred on the surface of a powdered compacted sample after desiccation at the end of a free swelling test, (Berdugo 2007) (see Figure 3b). Figure 3c corresponds to a sample at the end of a free swelling test on unconfined cores. During the test the sample swelled and was degraded. Gypsum crystals were found on existing crack surfaces. The clay matrix, divided by the active cracks, became severely damaged (Oldecop 2006). Swelling records measured in these tests are represented in Figure 5.

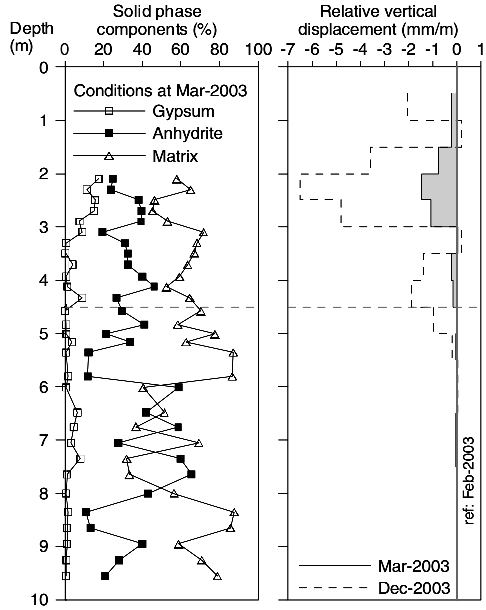

Figure 4. Characterization and vertical expansive profile of station 411+600 (invert-arch).

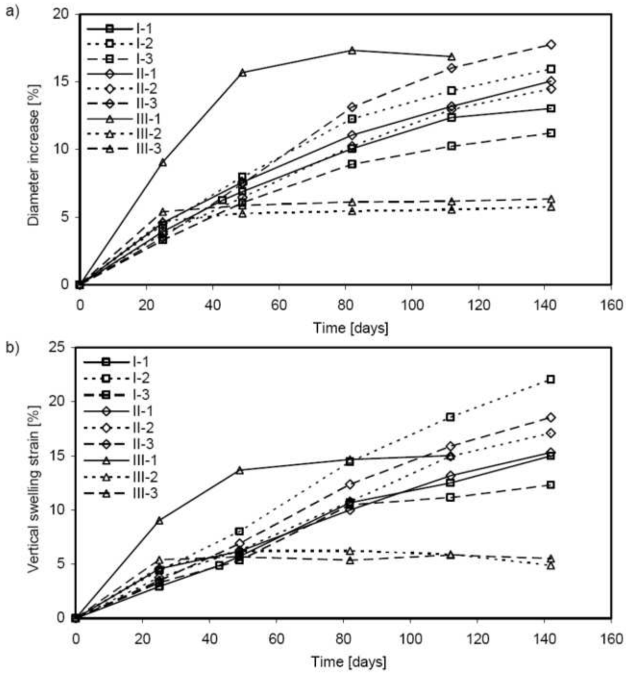

Figure 5. Swelling records for the tested specimens during free swelling tests. a) Diameter increase. b) Height increase (Oldecop 2006).

3 THE GYPSUM ROCK IN THE VICINITY OF THE TUNNEL

The magnitude of expansive phenomena in Lilla tunnel wasn't homogeneous along its length. There were sections with swelling displacements near 800 mm and other with minor swelling phenomena. Understanding this different expansive behaviour along Lilla tunnel would contribute to the development of practical criterion from geotechnical investigations.

Recently two new boreholes have been carried out in Lilla tunnel. Boreholes were performed from the natural surface of the terrain to 10 m below the floor level of the tunnel, a few meters away from the tunnel abutment wall. One borehole was located near a section with maximum swelling displacement, and the other near a section with minimum swelling displacement. The analysis of the boring records shows that in the location associated with maximum swelling (Borehole 1) a large proportion of striations and slickensided surfaces exist. If compared with Borehole 2, a much higher sulphate proportion in the rock (see Figure 6), dominated by anhydrite, was found. In addition, the ratio claystone/sandstone is higher in Borehole 1.

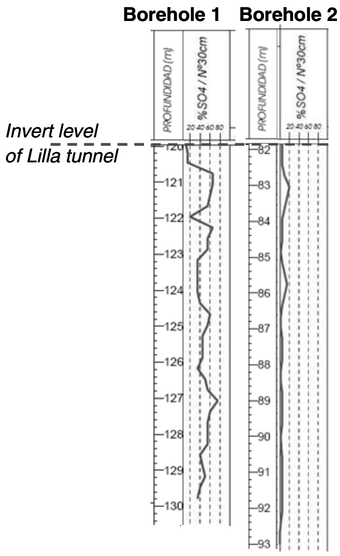

Figure 6. Sulphate proportion in the rock from a borehole located near a tunnel section with maximum (left) and minimum swelling phenomena (right).

Figure 7. Slickensided surface from Borehole 1 in Lilla tunnel.

4 MODELLING EVAPORATION PHENOMENA

The occurrence of gypsum crystal growth in open discontinuities is a characteristic of Lilla tunnel as well as other tunnels with expansive phenomena (Alonso et al. 2007). Crystal growth is at the origin of observed expansions in the active zone (Figure 3a). The expansive phenomena in sulphated claystones occur mainly on structural discontinuities (relict or induced by stress changes).

Crystal growth in fissures from sulphate-rich water is induced by two mechanisms: (i) the attainment of equilibrium in supersaturated aqueous solutions, and (ii) the evaporation of aqueous solutions, due to the relative humidity conditions imposed by the tunnel atmosphere. This mechanism leads also to supersaturation conditions. Gypsum crystallization in discontinuities contributes to the opening of existing cracks and to the occurrence of new ones, generating new surfaces where gypsum can crystallize. The added contribution of the isolated processes in opening the cracks results in the general expansive phenomena. Aggregations of gypsum crystals growing on discontinuities would produce a flat-jack effect pushing apart the rock mass, originating the heave of tunnel floor and high swelling pressures if heave is prevented. Apparently this process will be maintained while the gypsum crystallization occurs. Gypsum crystal growth is controlled by the continuous flow of sulphate-rich water, its concentration and the environmental conditions of the joints, which may result in a state of supersaturation.

Crystal growth, associated with the second mechanism mentioned, has been modelled within a general framework for thermo-hydro-mechanical analysis for saturated/unsaturated porous materials (Alonso and Olivella 2008). The hypothesis made to calculate the mass of precipitated crystals is that the pore water is saturated in sulphates. Then any evaporation results in a precipitated mass. These developments were included in the general Finite Element program for THM analysis CODE-BRIGHT (DIT-UPC 2000). One example of calculated vertical strains from crystal growth induced by evaporation at the tunnel boundary is presented in Figure 8. Calculated vertical swelling follows the patterns observed in the field by means of high precision extensometers; however computed swelling is lower than measurements.

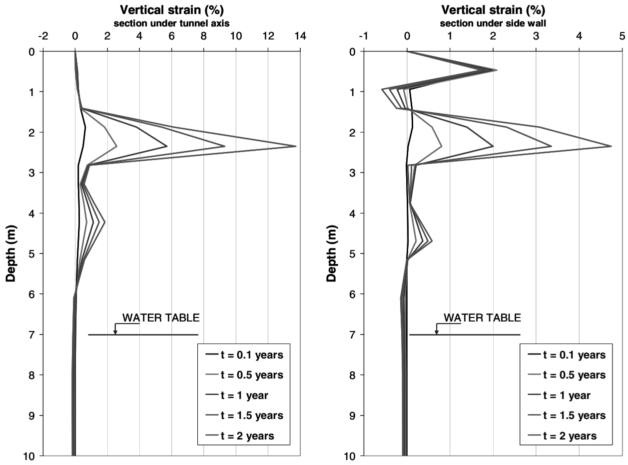

Figure 8. Vertical strains in two vertical sections. A) Under tunnel axis; B) Under the side wall.

5 ADDITIONAL PHENOMENA LEADING TO CRYSTAL GROWTH

Evaporation of sulphated water is not the unique cause of gypsum crystal growth in discontinuities. A number of studies indicates that gypsum crystal growth can occur in absence of evaporation. Spontaneous precipitation of calcium sulpate, mainly of calcium sulphate dihydrate (gypsum), from highly supersaturated solutions, and its seeded crystallization at low supersaturations have been reported (Kontrec et al. 2002). Experiments show that equilibrium solubilities of gypsum and anhydrite, for 20ºC, are $15.5 \cdot 10^{-3}$ mmol cm^{-3} and $21.0 \cdot 10^{-3}$ mmol cm^{-3} respectively (Kontrec et al. 2002). Then the equilibrium concentration of calcium sulphate (in solution) in the presence of gypsum is lower than the equilibrium concentration in the presence of anhydrite. This situation will result in gypsum precipitation.

It is therefore accepted that crystal growth is a consequence of groundwater supersaturation in sulphate content. Supersaturation is achieved when water flowing in discontinuities dissolves anhydrite. Since the concentration of sulphates in water in equilibrium with anhydrite exceeds the gypsum saturation concentration, gypsum crystals will precipitate. The experimental work developed by Kontrec et al. (2002) shows the kinetics of the transformation of anhydrite into gypsum in an aqueous media. The transformation process was found to be solution-mediated, and it was described by a mathematical model.

Since these phenomena will take place in a fractured material (the claystone), crystallization will result in stress development and cracking depending on the characteristics of the rock mass and the flow and equilibrium conditions of the sulphated water. An upper bound on the crystallization pressure is set by the supersaturation of the solution (Scherer 1999).

6 MODELLING

A theoretical model that reproduces crystal growth in a porous media from supersaturated aqueous solution has been developed. The solid mass balance has been modified to include the basic mechanisms of anhydrite dissolution and gypsum precipitation in order to represent gypsum crystal growth. The balance equations implemented allow defining the variation in porosity, which depends on the volumetric strain rate and volume variation induced by mass of precipitated crystals. In addition, the precipitated mass of gypsum induces swelling strains which are taken into account. The kinetics of dissolution/precipitation is described in the solute mass balance by mean of rate equations, which depend on undersaturation or supersaturation of the aqueous solution. The formulation was implemented in the general purpose Thermo-Hydro-Mechanical and Chemical Finite Element code CODE_BRIGHT (DIT-UPC 2002). The complete formulation is described in detail in a publication in process.

7 SOME RESULTS

It has been assumed that the material under the floor level of Lilla tunnel is confined laterally, and displacements develop only on the vertical direction. This is an approximation to the boundary conditions imposed by the excavation of the tunnel (free boundary condition in displacement at the floor level). Therefore, the behaviour of Lilla tunnel foundation material is similar to an oedometer test. A column of tunnel foundation material, located in the active zone, has been modelled in plane strain conditions. One dimensional vertical flow of water has been imposed, representing the upward flow towards the flat-slab of the tunnel.

The calculated vertical displacements in time are compared in Figure 9 with flat-slab "in situ" measurements for some Lilla tunnel sections. Case 1 to Case 4 correspond to a model with a 5 m deep active zone. Model parameter calibration has been done in order to obtain results in the range of measurements. The four cases represented correspond to different rates of dissolution/precipitation and different ratios between crystal mass precipitated and induced strains. The model is able to capture the set of field heave records.

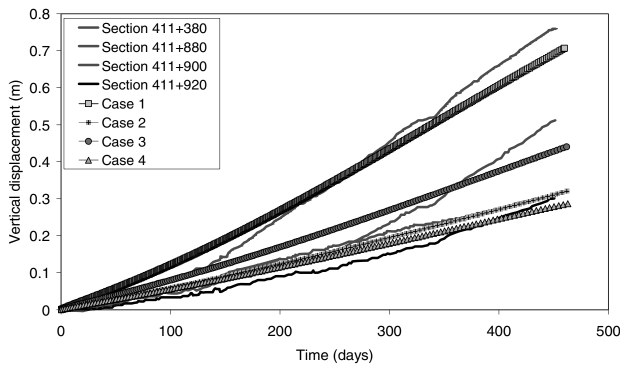

Figure 9. Calculated (Case 1 to 4) and measured vertical strains (Sections) on the flat-slab surface of Lilla tunnel.

8 CONCLUSIONS

Field observations in Lilla tunnel indicate that swelling deformations and swelling pressures are due to gypsum crystal growth.

Gypsum crystals develop because of sulphate supersaturation conditions. These conditions occur when water circulating in discontinuities dissolves anhydrite. Evaporation in the exposed boundaries of the tunnel may also contribute to supersaturate the natural water and, therefore, to set out a crystal growth process.

A theoretical model consistent with field and laboratory observations has been developed. It has been included into a general purpose Finite Element code for Thermo-Hydro-Mechanical and Chemical analysis of porous materials (Code_Bright). A simulation of Lilla tunnel conditions has been performed. Field data on tunnel floor heave are reproduced by the model. The tool developed is believed to constitute a step forward in the analysis and prediction of swelling phenomena in sulphate bearing clay rocks.

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