Abstract of the Thesis:

Expansion mechanisms in sulphated rocks and soils

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1. INTRODUCTION

Geological formations containing sulphates are commonly associated with the development of severe expansions when they are involved in tunnel excavation. The intensity of the observed expansive behaviour in these materials is greater than in other expansive soils and rocks free of sulphates. Swelling in sulphated rock formations can also occur in other scenarios and also within fills made of compacted material from excavations in sulphated rocks. The functionality and stability of engineering works are affected in the majority of the known cases.

The prediction of strains and swelling pressures in sulphated formations is a difficult task. On that direction, the Thesis analyses and describes the mechanisms and conditions leading to expansions in sulphated rocks through the compilation of real cases showing the presence or absence of swelling phenomena and the detailed investigation of three exceptional cases of damage induced by expansions involving sulphated formations in Spain: Lilla tunnel, Pont de Candí bridge and Pallaressos embankments.

Mechanisms leading to swelling in tunnels in sulphated rocks have been described in the literature; however, an alternative interpretation is proposed in the Thesis. In the first two cases the development of swelling phenomena is explained by the precipitation of gypsum crystals in rock discontinuities. The maximum pressure exerted by crystal growth has been estimated under a thermodynamical analysis. A coupled Hydro Mechanical and Chemical model formulated in a porous media has been developed to simulate volumetric expansions explained by gypsum precipitation. The model has been validated against the heave experienced by Pont de Candí viaduct. Expansions in the third case analysed are a result of massive growth of ettringite and thaumasite minerals in embankments reinforced by Portland cement due to sulphate attack to cementitious materials. A simulation of the chemical reactions involved in sulphate attack and a finite element model of embankment swelling has been developed.

2. EXTREME EXPANSIVE PHENOMENA IN LILLA TUNNEL

Lilla tunnel belongs to the high-speed railway from Madrid to Barcelona. The tunnel crosses a sulphated claystone formation of Eocene age. A singular aspect is the existence of a persistent system of low-angle slickensided surfaces resulting from a tectonic activity. The tunnel has a length of 2Km and it was excavated initially with a horse shoe cross-section. Its overburden varies between 32 and 110 meters. The excavation of the tunnel was performed mainly by drill and blast from two portals, dividing the section into head and bench.

Heave at the floor level of the tunnel was detected just after the construction of the flat slab and evolved in time at high rates without any signs of stabilization. The abutments and the crown were not affected by ground expansion. The material crossed by the tunnel is constituted by a clayey matrix composed by non-expansive clays and a crystalline fraction chiefly made up of gypsum and anhydrite. Water level close to the tunnel floor was found in boreholes drilled from the flat slab and from the invert. A maximum heave of 800 mm was measured in one section with flat slab after 13 months of measurements. Maximum values of swelling pressures recorded by means of stress cells installed at the concrete/claystone interface in test sections under invert were close to 5 MPa.

The strain records measured along boreholes indicated the existence of an upper “active” zone where swelling strains were concentrated in a rock thickness of 4-5 m. Growth of small thin monoclinic gypsum crystals and gypsum grouped in “rosettes” were found in several claystone discontinuities in all the cores recovered from the active zone below tunnel floor.

Expansions in Lilla tunnel led to the reconstruction of the tunnel. A highly reinforced circular cross-section was built along the entire tunnel. Maximum recorded swelling pressures during the subsequent operational stage, recorded in pressure cells installed at the rock/lining interface at invert, stayed between 5-6 MPa.

Tunnel monitoring during construction and operation has shown that there is a variability of the recorded intensity of swelling along the tunnel and also in a given section (Figure 1). The detailed analysis of recovered cores from areas with different swelling intensity has indicated that the conditions that favour the development of sulphate-induced expansions in Lilla tunnel are: a significant proportion of sulphate minerals (especially anhydrite), certain rock damage (presence of sheared discontinuities) and a significant presence of clay.

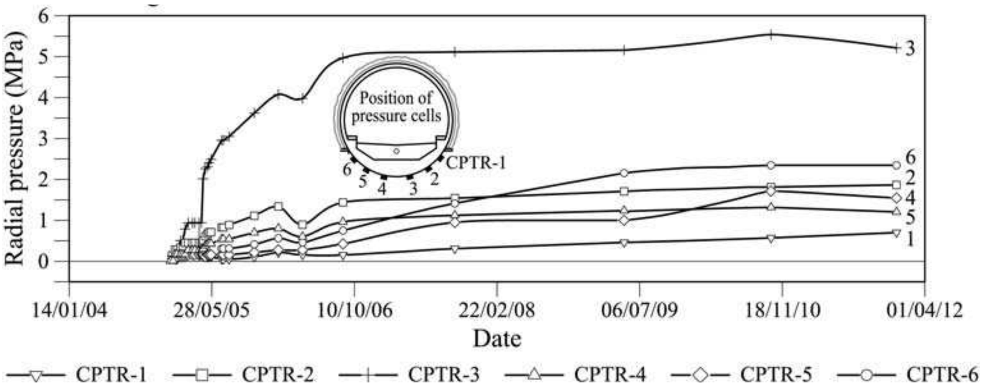

Figure 1. Maximum radial pressures recorded during tunnel operation in one section

3. HEAVE OF PONT DE CANDÍ BRIDGE

Pont de Candí bridge is placed in the vicinity of the North portal of Lilla tunnel, also in the high-speed railway Madrid-Barcelona. The bridge deck is 413 m long and is supported by 9 long pillars. Each viaduct pillar is supported by a group of 9 large bored piles, 1.65 m in diameter and 20 m long on average. The 4 central pillars of the bridge are founded in a rigid stratum of anhydritic claystone formation, the same formation crossed by Lilla tunnel.

A sustained heave was detected at the central pillars of the bridge after the end of construction. Vertical displacements accumulated at high rates ranging from 5 to 10 mm/month. Pillars were also experiencing small rotations and horizontal displacements.

A monitoring campaign of the structure and the subsoil was designed. A maintained heave of the ground surface was measured in an area 200 m wide centred along the axis of the bridge. In general, the most significant heave was measured in an area around the central pillars of the bridge. Long continuous extensometers installed near the central pillars of the bridge identified the development of swelling vertical strains in an active layer 12-15 m thick located below the tip of the piles. The comparison between the vertical distribution of anhydrite and gypsum contents, obtained by means of X-ray diffraction analyses, and the recorded swelling strains showed that expansion was directly associated with the presence of anhydrite. The presence of gypsum crystal growth was observed on some open discontinuities in the material recovered from depths corresponding to the active expanding layer.

Tensile fissures were found at the pile-cap contact of the 4 central pillars of the bridge. A semi-analytic analysis of a pile group swelling interaction justified that cracks in the cap-pile contacts were the result of the development of a non-homogeneous heave displacement of the pile group capped by a rigid slab.

A hydraulic cross-hole campaign performed on 3 boreholes, situated in an area with high heave near pillar 5 showed that the active expanding layer had a system of open hydraulically connected horizontal discontinuities. No hydraulic connection could be established in a vertical direction.

To remediate the heave of the structure an embankment was built partially filling the valley of the viaduct. The rate of measured heave on the structure after the construction of the embankment decreased. Sliding micrometers measured a decreasing rate of vertical strains in the active layer after the construction of the embankment.


(a) (b)

Figure 2. Gypsum crystal growth in recovered cores from boreholes at depths corresponding to the active layer a) needles filling partially a discontinuity, b) laminar gypsum crystal growth developing inside the clay matrix

4. THE SWELLING MECHANISM

Field and laboratory observations indicate that the swelling detected in the active expanding layer is related with gypsum crystal growth in open fractures. Gypsum crystals precipitate from supersaturated water in calcium sulphate. Since the solubility of anhydrite ($CaSO_4$) is higher than the solubility of gypsum ($CaSO_4 \cdot H_2O$) below 56ºC, water in contact with the anhydritic claystone at active layer will dissolve anhydrite. Then, this water will be supersaturated with respect to gypsum and the excess of dissolved calcium sulphate will tend to precipitate in gypsum crystals. In practice, supersaturation is achieved when water flowing through discontinuities dissolves anhydrite (Fig.3). The process of precipitation of crystals in discontinuities is thought to act as a local jacking effect pushing apart the rock mass, capable of opening discontinuities and inducing swelling strains. Maximum swelling pressures of 8.40MPa and 16.80 MPa due to crystal growth have been estimated on theoretical grounds.

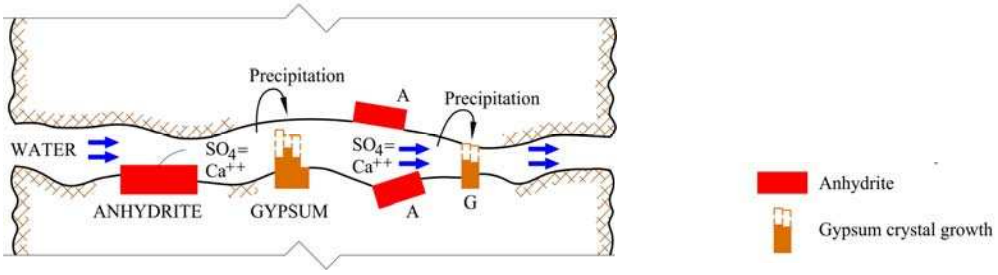

Figure 3. Conceptual model for gypsum precipitation.

The stress release under the horizontal tunnel floor in Lilla tunnel induced by the excavation of the tunnel was capable of opening the existing slikensided surfaces and also new discontinuities, allowing the flow of water in discontinuities of the sulphated claystone.

The development of the swelling phenomena in depth in the area of Pont de Candí bridge is thought to be associated with the construction of the bridge. The boreholes drilled at the beginning of the design stage and later the construction of the piles connected the upper aquifer with the deep fractured claystone. The water inflow into the horizontal open fractures triggered the swelling phenomena.

5. MODELLING GYPSUM CRYSTAL GROWTH AND HEAVE

5.1 Model formulation

The swelling phenomena have been modelled within a general framework for coupled thermo-hydro-mechanical analysis for porous materials. The presence of two soluble species (anhydrite and gypsum minerals) and one non-soluble species (clay matrix and other non-soluble minerals) has been taken into account in the formulations. The mass balance equation for the solid phase formulated allows defining the variation of porosity, ϕ:

$$\frac{D_s\phi}{Dt} = \left(1-\phi\right)\nabla\cdot\left(\frac{d\mathbf{u}}{dt}\right) - \frac{1}{\rho_{gyp}}\frac{dm_{gyp}}{dt} - \frac{1}{\rho_{anh}}\frac{dm_{anh}}{dt} \qquad (5.1)$$

as a function of the volumetric strain rate induced by solid displacements, $\boldsymbol{u}$, and the volumetric rate of precipitated or dissolved mineral crystals (m_{gyp}, m_{anh}). ρ_{gyp} y ρ_{anh} are gypsum and anhydrite densities. Two kinetic equations (one for each soluble mineral) have been formulated to describe the rate of precipitated or dissolved mass of anhydrite and gypsum crystals. They depend mainly on the “degree” of supersaturation or undersaturation of water in sulphates. The formulation takes into account that gypsum crystals incorporate water molecules in its crystalline structure when they precipitate. The strains induced by precipitation of gypsum are considered as imposed “external” strains in the momentum balance equation of the medium. They are calculated from the amount of precipitated gypsum and from the prevailing stress acting on crystals.

$$\frac{d\varepsilon_i}{dt} = \frac{\gamma_i}{\rho_{gyp}}\frac{dm_{gyp}}{dt} \quad , \quad i = 1,\ 2,\ 3 \quad ;\ 1=\mathit{Vertical}\ (z)\ \ ;\ 2,\ 3=\ \mathit{Horizontal}\ (h) \qquad (5.2)$$

the parameter γ_i is a coefficient that takes into account the effect of the stress applied on crystals on the strains induced by precipitation. A solute mass conservation equation has also been formulated to keep track of calcium sulphate solute.

These formulations have been included in the Finite Element program for coupled thermo-hydro-mechanical analysis in porous media CODE BRIGHT (Olivella et al. 1996).

5.2 Heave calculations. Comparison with field data and sensitivity analysis

A column of foundation material of the central pillar of the bridge has been simulated. The flow conditions in the active layer have been reproduced. The fractured and high permeable sulphated claystone has been modelled as a porous material with a high porosity. The calculated response of the model seems to be consistent with heave records observed in a relatively long period (4 years). The model can also reproduce the effect of the construction of an embankment over the surface of the valley on the heave rate.

A sensitivity analysis performed indicated that the initial anhydrite and gypsum content, the value of the equilibrium concentration at saturated conditions with respect to anhydrite and gypsum and, essentially, the confining stress have a relevant effect on the swelling strains calculated in the model.

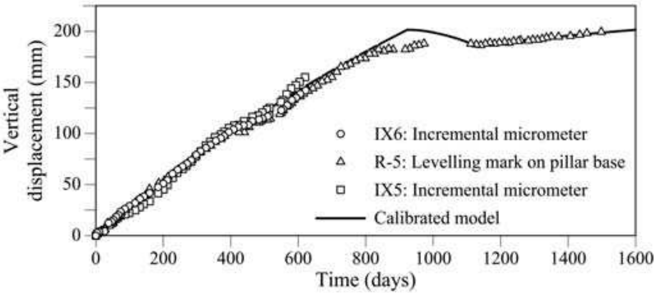

Figure 4. Measured and calculated surface heave.

6. ANALYSIS OF MASSIVE SULPHATE ATTACK TO CEMENT TREATED COMPACTED SOILS

Two access embankments to a bridge in the Madrid-Barcelona high-speed railway line, having a maximum height of 18 m, experienced a continuous and severe heave near the abutments shortly after construction. Vertical displacements reached 120 mm in a 2 year period. The embankments included soil-cement treated transition wedges. A grid of 10 m deep jet-grouting columns was also built with the purpose of stabilising the embankments. Instead, a sustained swelling deformation, which extended to depths of 8-10 m, was activated. Field instrumentation showed that a volumetric swelling was deforming the embankments. The compacted soil was low-plasticity clayey material with a variable percentage of gypsum, it was excavated from nearby cuts in gypsiferous Tertiary claystones.

Long term free swelling tests were performed on undisturbed and compacted samples prepared with the material recovered in boreholes. Swelling evolved in time in all the samples tested without signs of levelling off. Ettringite and thaumasite crystals were found within the expanding levels and in the long term tested samples. The embankments and the track base suffered a massive sulphate attack, which was triggered by the simultaneous presence of cement, clay, sulphates and an external supply of water (rain).

A simulation of the hydraulic and chemical processes taking place at the compacted soil-cement interface was performed. Calculations showed that expansions in this type of embankments would proceed for a long time because of the availability of the necessary components for ettringite and thaumasite formation.

A finite element model of embankment swelling indicated that a dangerous state of passive stresses had been developed on the upper 8-10 m of the embankment. A total force against the bridge abutments of 2.32MN/m, induced by swelling of embankments, was calculated.

7. CONCLUSIONS

The mechanism that explains the expansions in sulphated formations is really a question of reaching supersaturated conditions in calcium sulphate dissolved. Dissolution of anhydrite results in supersaturated conditions with respect to gypsum since the solubility of anhydrite is higher than the solubility of gypsum. This is believed to lead to large expansions observed in the cases described. The presence of fractures in the rock favours the precipitation of gypsum when water and anhydrite are present.

A model has been developed for simulating the expansions in sulphated rocks due to gypsum crystal growth. The presence of soluble sulphated minerals and the occurrence of precipitation and dissolution of crystals have been considered in the formulations. The sensitivity analysis performed indicated that the initial mineral content, solubility of gypsum and anhydrite and, especially, the confining stress have a relevant effect on the swelling strains calculated. The simulation of gypsum precipitation and expansions has been successful in Pont de Candí.

Although sulphate attack is known in treated compacted layers with lime or cement, the phenomenon has been analysed in the case of a massive attack to embankments, which implies large pressures against bridge abutments.

8. REFERENCES

Olivella, S., Gens, A., Carrera, J. & Alonso, E. E. (1996). Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media, Engng. Comput. **13**: 87-112.