

# The role of rock damage in the development of expansions in anhydritic claystone formations

**Anna Ramon, Eduardo E. Alonso**

*Dept. of Civil and Environmental Engineering, Universitat Politècnica de Catalunya - BarcelonaTech (UPC), Barcelona, Spain. [anna.ramon@upc.edu](mailto:anna.ramon@upc.edu)*

*Centre Internacional de Metodologies Numèriques a l'Enginyeria (CIMNE), Barcelona, Spain*

**ABSTRACT:** The development of expansions in anhydritic formations occurs often when they host the construction of an infrastructure. The expansions are very intense and typically develop in a sustained manner over time, without any signs of stabilization. Some field records illustrate the phenomenon: the heave rate of Lilla tunnel flat slab amounted to 2mm/day, and measured swelling pressures reached 7 MPa against the rigid invert. Anhydritic formations also may show severe expansions when they involve foundations. This is the case of the uplift of the historical centers of two towns in France and Germany. Another example is the singular case of a long railway viaduct, founded in an anhydritic formation in Spain, that suffered a maintained vertical displacement at speeds ranging from 5 to 10 mm/month. This swelling behavior results often in a severe damage to the involved structures. The precipitation of gypsum crystals in discontinuities of the soil and rock masses explain the development of expansions observed in the field. The main processes involved during swelling are identified. The presence of water is a well-known requirement for the occurrence of expansions. However, it is difficult to predict if expansions will occur and, also, to estimate the swelling intensity and its evolution over time. A key factor to trigger the expansion mechanism is the damage induced in the geological formation by the construction works, such as excavations. The case histories described illustrate these conclusions.

**KEYWORDS:** damage, expansions, anhydrite, crystal, chemical reactions, tunnels, foundations.

## 1 INTRODUCTION

The development of expansions is a common phenomenon that occurs in the rock mass when infrastructures are built in anhydritic rocks. Tunnels and underground excavations are the typical and known infrastructures affected by this type of expansions. Published papers describe in detail several cases of tunnels in central Europe that are damaged by severe expansions when they cross Mesozoic anhydritic formations. They are found typically at the North of Switzerland and the South of Germany. In all the cases they involve Keuper and “Anhydritgruppe” Tertiary formations (Kovári et al., 1988; Einstein, 1996; Steiner, 2020; Wittke, 2006; Anagnostou, 2007; Alonso et al., 2013; Serafeimidis & Anagnostou, 2014; Wittke et al., 2017; Steiner & Schwalt, 2019). In contrary, in Spain, the cases of significant damaging expansions in tunnels involving anhydritic rocks show up often in Tertiary formations, like the Eocene, and also in Keuper Triassic formations (Alonso et al., 2013; Ramon et al., 2017; Alonso et al., 2023). The swelling in anhydritic rocks is one order of magnitude more intense than the clay-related swelling in soils and rocks. In the known cases of tunnels damaged the expansion results in a rapid uplift of the tunnel floor, with rates ranging up to 1 – 2 mm/day, and in the failure of the tunnel flat slab. Rock expansion causes the development of high swelling pressures against the tunnel lining when the cross section of the tunnel is rigid, for example, when the lining follows a resisting support design. A maximum swelling pressure close to 7 MPa was recorded in a pressure cell installed against the rigid circular lining of Lilla tunnel. The case of Lilla tunnel is analyzed in more detail afterwards.

Damaging expansions in anhydritic rocks can also involve buildings and foundations. One example is the singular sustained uplift suffered by buildings of the historic center of Staufen, built over Keuper geologic Alpine formations in the South-West of Germany (Sass and Burbaum, 2010; Ruch and Wirsing 2013; Schweizer et al. 2019). The continuous heave of the ground, at maximum rates up to 11 mm/month, generated important structural damage to the historical buildings. The Spanish viaduct Pont de Candí and a building near Barcelona founded on Tertiary and Triassic anhydritic formations (Alonso & Ramon, 2013; Ramon & Alonso, 2013; Alonso et al., 2015;

Ramon & Alonso, 2018) are other examples of infrastructures affected by anhydritic expansions.

The mechanisms of expansive behavior in anhydritic rocks are understood in general terms. However, a more fundamental explanation for the triggering of expansion is analyzed here. Excavations in anhydritic rocks do not always result in expansions. The relevance of damage in the rock mass to trigger the development of the phenomenon is explained by addressing the role of “free space” generated in the rock to allow gypsum precipitation.

This paper concentrates first on the necessity of the presence of certain “available” space in the rock for crystal precipitation. Then, it provides evidence of the role of rock damage in three real cases affected by anhydrite-related expansions. The attention is focused on the necessity of certain degree of damage in the rock for the triggering of swelling phenomena.

## 2 RELEVANCE OF SPACE AVAILABILITY IN ANHYDRITIC EXPANSIVE MECHANISMS

Swelling in rocks containing anhydrite is originated by the precipitation and growth of crystals of gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) in open discontinuities of the rock (Alonso et al., 2013; Ramon & Alonso, 2013). The precipitation of gypsum in fractures exert pressure against the surfaces of the fracture, capable of opening further the discontinuities. This mechanism leads to swelling strains and, also, the swelling pressures observed in the field. Gypsum crystals precipitate from water that is supersaturated in calcium sulphate with respect to gypsum. Therefore, the presence of water is a necessary condition for the development of expansions. The explanation for the attainment of sulphate supersaturation conditions in the groundwater is presence of anhydrite ( $\text{CaSO}_4$ ) in the rock. Therefore, the precipitation of gypsum in anhydritic rocks doesn't require evaporation boundaries.

Figure 1 backs up this concept. The figure represents the values of equilibrium concentrations of dissolved calcium sulphate with respect to both gypsum and anhydrite minerals for different temperatures. Since anhydrite is more soluble than gypsum for 15° (Figure 1), which is a reasonable temperature in known cases, water in contact with the anhydritic rock will

dissolve anhydrite and the water will reach supersaturation conditions with respect to gypsum. Then, the achievement of chemical equilibrium will result in the precipitation of the excess of calcium sulphate in gypsum crystals.

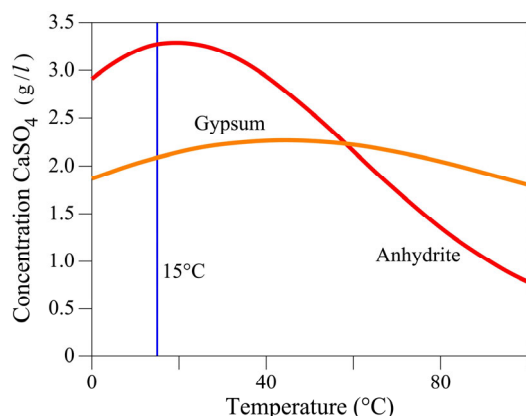


Figure 1. Evolution of Gypsum and Anhydrite solubilities for different temperatures.

The occurrence of precipitation of gypsum crystals requires also the presence of available “open” space where crystals of gypsum can nucleate and grow. In rocks, the space can be provided by pores, fractures, and also cavities or flaws of the rock.

Scherer (1999), discussing the growth of crystals in pores, stresses that cracks and pits are sites which favor the nucleation of crystals. The nucleation of gypsum requires enough space for the formation of the crystalline nucleus. The minimum pore size to allow the precipitation of gypsum crystals depends on several factors, i.e. the saturation of the solution, the temperature and the kinetics of crystal nucleation. The precipitation of crystals in small rock pores is influenced by the pore-size-controlled solubility (PCS) phenomenon. PCS describes the thermodynamics of the relationship between mineral solubility and pore size. Emmanuel & Berkowitz (2007) and Emmanuel & Ague (2009) explain, based on the PCS, that preferential precipitation of salts occurs in larger pore volumes, in the sense that it is possible that a solution could be supersaturated in large pores while being undersaturated in small pores. Putnis (2015) analyses the role of porosity and supersaturation of fluids in pores, in controlling nucleation and growth of secondary minerals in the pore spaces. He pays attention to the limitations of crystallization from solutions filling small pores. He refers to the PCS to conclude that in very small pores (sizes smaller than 1 micron), crystals will be more soluble and that this could avoid the precipitation in the small pores, and favor the precipitation in bigger ones. These ideas agree with the probabilistic behavior of the nucleation of crystals in porous media. In this regard, Prieto (2014), in his study about nucleation and supersaturation conditions in porous media, based on precipitation experiments and theoretical calculations considering classical nucleation theory, highlights that the pore-size influence on the nucleation results in the inhibition of precipitation in nanopores ( $\phi=8-30$  nm) and the preference for the precipitation in macropores ( $\phi=30$   $\mu$ m).

Investigations on the durability of stone materials against salts crystallization analyze the influence of pore size distribution in gypsum precipitation, and show that gypsum crystallization can occur in micrometric pores (Benavente, 2002). Charola et al (2007) in their review of gypsum crystallization and its effect in the deterioration of natural stones, refers to observations of gypsum crystal growth in natural pores. They also stress the tendency of gypsum to accumulate and to generate internal stresses in the rock, which

enhances deterioration. They mention the size of crystals as observed through microscopy and mention values in the range of microns.

Measured pore sizes of undamaged Lilla claystone are in the range of a few nanometers (Pineda et al, 2014). Figure 2 shows the pore size distribution of the undisturbed claystone of the rock mass of Lilla tunnel. Therefore, they are not big enough to allow the precipitation of gypsum crystals. However, cracks, slickensides and fissures have sizes many orders of magnitude larger (10000 nm = 10 microns). These defects seem more able to “attract” gypsum crystallization because of their shape and size. Consistent with these results, free swelling tests on unconfined cores showed the swelling and degradation of the tested samples (Oldecop & Alonso, 2012). Gypsum crystals were found on existing crack surfaces at the end of the tests. The clay matrix, divided by the active cracks, became severely damaged and degraded.

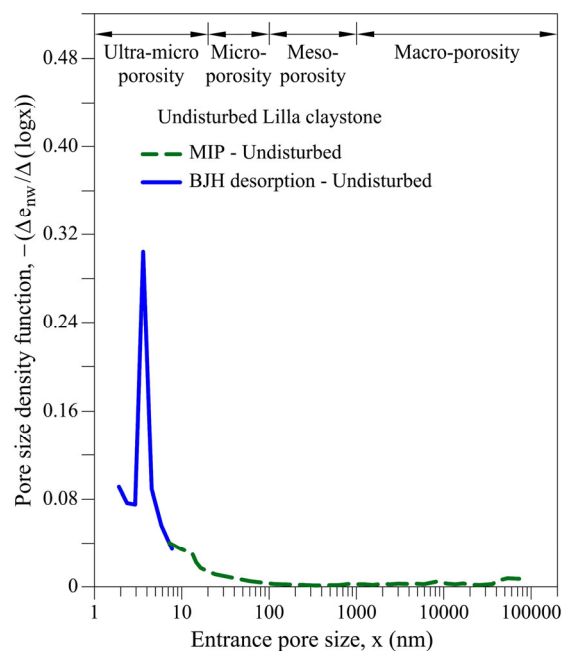


Figure 2. Pore size distribution of undisturbed Lilla tunnel claystone.

The following sections describe the lessons learned during the study of three real cases affected by expansions in anhydritic rocks. The three real cases demonstrate the importance of the damage in the rock for the triggering and development of expansions induced by gypsum crystal precipitation.

### 3 HEAVE OF A NUCLEAR POWER STATION

The Nuclear Power Station (NPS) experienced a sustained heave that was noticed at an early time during its construction in 1976. The heave was recorded over time by topographic marks installed in all the buildings. Vertical displacements up to 12 cm were measured at several points of the buildings during 25 years of monitoring (Figure 3). In addition, heave measurements indicated that some buildings had experienced some tilting.

The construction of foundations, preceded by a large excavation performed by blasting, reached a maximum depth of 70 meters in some areas. Horizontal large foundation platforms were created at different elevations. Figure 3 represents the distribution of the depths of excavation carried out. The magnitude of the large excavation performed is represented in Figure 4. The large excavation created large “basins” in the site

of the NPS that were difficult to drain. As a consequence, a phreatic level was established in the excavated areas, fed by the rain.

The NPS is founded on a reddish claystone of Eocene age with horizontal sedimentation planes at spacings of 1 - 4 m. Figure 4 shows the horizontally layered claystone in the exposed surfaces of the excavated slopes. Undisturbed samples of the foundation claystone exhibited high unconfined compressive strengths (30-40 MPa). In high quality cores recovered in boreholes the rock has a massive aspect. Minerals found in cores are quartz (10%), calcite and dolomite (50-70%), clay minerals (10-20%), anhydrite in proportions ranging from 0 to 30% (average around 10%) and a gypsum content decreasing from 20 - 30% in upper elevations to low values at depth. Among the clay minerals, illite dominates (10%). High suctions were found in recovered cores. This rock changes into a weathered material at shallow depths.

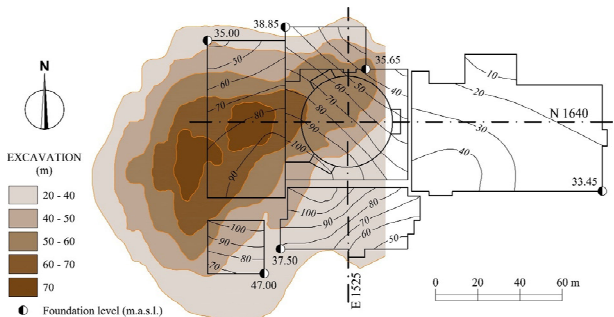


Figure 3. Contours of equal heave (mm) in NPS buildings (1979-2001) and depths of the large excavation performed during construction.

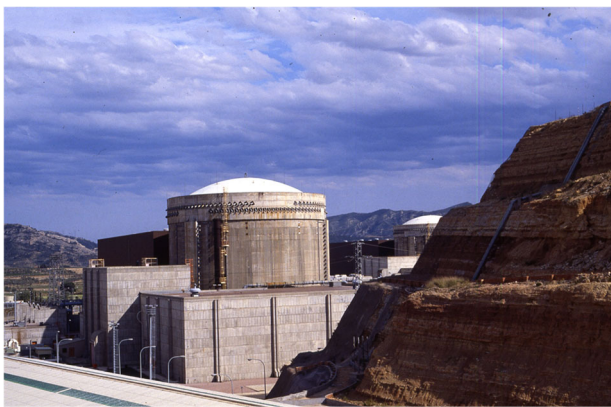


Figure 4. Containment building and excavated slope in the Tertiary claystone.

High precision continuous extensometers installed in boreholes identified the development of expansions within an active expanding layer 5-15 meters thick. Its lower limit was roughly parallel to the upper rock horizontal surface generated after excavation. Measured heave of the buildings agrees with the accumulated strains recorded along depth in extensometers.

Figure 5 shows the typical pattern of vertical strains and their evolution over time observed in the extensometers installed. The monitoring records of vibrating wire piezometer also provided valuable insight for the understanding of the expanding phenomenon. Some piezometers measured negative water pressures, indicating the presence of suction. Some of them were installed inside the active expanding layer identified by the extensometers. However, other piezometers recorded positive water pressure, and, in several occasions, the

measurements agreed with the phreatic level established in the excavated area. This was an interesting piece of information to understand the heave phenomena because it shows that, in the active expanding layer, there exists a group of fractures that contain water under pressure. The point that the fractures are hydraulically connected with the phreatic level generated after the excavation, is also very relevant for the general understanding of the swelling phenomena, because this indicates that at those depths water is arriving for the first time, in a significant recent period of time in geological terms. This suggests that the intense unloading associated with the large excavation damaged the upper levels of the claystone and, as a consequence, horizontal fractures developed.

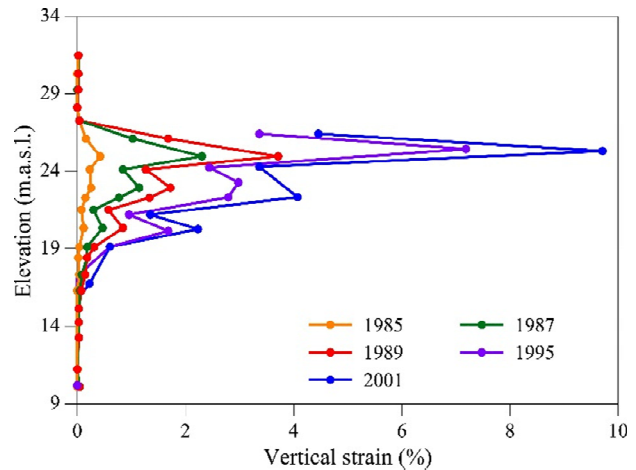


Figure 5. Distribution of swelling deformation recorded by a continuous extensometer.

The presence of anhydrite in the claystone, the observations of gypsum crystals in specimens after long time tests, the existence of fractures containing water in the active expanding layer, and the parallelism with other cases involving expansions in anhydritic formations suggest that gypsum precipitation in fissures had a significant role in explaining long term heave in the NPS. Recent numerical simulations calculated with a thermo-hydro-mechanical FE code verified that the stress discharge associated with the large excavations resulted in tensile stresses capable of opening fractures, most probably at the location of sedimentation planes. In addition, fracture opening, capable of maintaining positive water pressures connected with established water levels, were thick enough to allow the precipitation of gypsum crystals. The relevant point in this case is the evidence of the importance of the rock damage in triggering the heave. There is no evidence of heave in the NPS site before the construction works. The heave is a direct consequence of the construction.

#### 4 EXPANSIONS IN LILLA TUNNEL

The high-speed railway Lilla tunnel is well known for the intense severe expansions suffered and the detailed studies carried out during its construction and operation periods (Alonso et al., 2013; Ramon et al., 2017; Alonso et al., 2023). In particular, the large in-situ investigation carried out to understand the expansion phenomenon and to define the design of the final cross-section and lining of the tunnel is very relevant.

The tunnel crosses an anhydritic-gypsiferous claystone formation of Eocene age which contains a persistent system of low-angle slickensided surfaces resulting from an ancient tectonism. The overburden varies from 32 to 110 meters and the

tunnel was excavated initially with a horse-shoe cross section along its 2 km length by means of a drill and blast procedure.

A generalized heave at the floor level of the tunnel was detected just after the construction of the flat slab in September 2002 and evolved in time at high rates up to 80 cm in 13 months without any signs of stabilization (Alonso, et al., 2013). Continuous extensometers installed along boreholes drilled below the tunnel floor identified that heave was originated by the development of expansions over time within an upper active layer located below the tunnel floor (Figure 6). The thickness of this active zone remained basically unchanged during the monitoring program. Boreholes drilled from the tunnel floor showed the presence of water level close to the tunnel floor.

Growth of gypsum crystals was found in several claystone discontinuities in cores recovered from the active zone below the tunnel floor. It was clear that precipitation of gypsum crystals at discontinuities was at the origin of expansions measured in the active layer below tunnel floor.

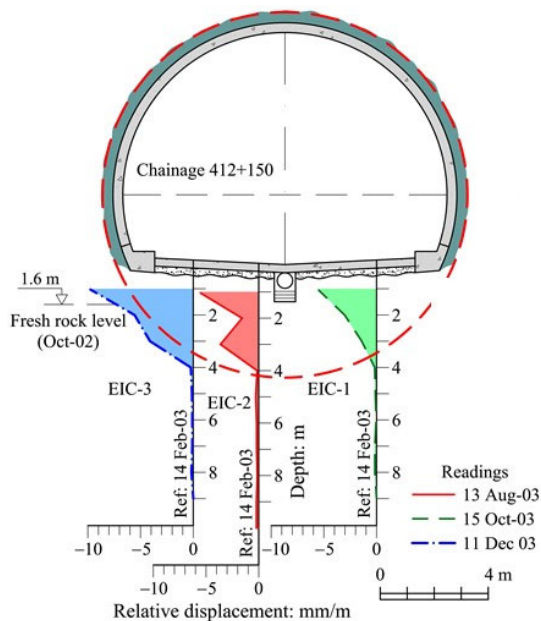


Figure 6. Recorded expansions below the tunnel flat slab by continuous extensometers.

The works carried out for the excavation of Lilla tunnel defined the triggering expansion scenario in the rock mass. The large overburden of the tunnel implies that the excavation of the tunnel produced an important stress relief that resulted in rock damage. The tunneling-induced stress changes resulted in the opening of the existing tectonic slickensided surfaces and also new fractures in the rock mass. The opening of discontinuities generated an increase of permeability and, therefore, facilitated the presence of water, a requirement for precipitation of gypsum crystals. In addition, the generation of fractures provided the necessary space for gypsum precipitation. The excavation procedure by means of explosives contributed also to open additional discontinuities and intensified the damage of the rock.

Damage induced by stress relief in tunnels typically concentrates below the tunnel floor along a depth similar to the radius of the tunnel. The observed heave led to modify the geometry of the cross section into a circular one. Figure 6 suggests that the additional excavation would remove the active expanding zone and the heave problem would be circumvented. However, extensometers identified that an active expanding layer, 4 to 6 m thick, was reproduced again below the tunnel

invert (Figure 7). Swelling pressures increasing in time, were measured at the invert-rock contact. Maximum swelling pressures, in the range 5-6.5 MPa, were recorded during the subsequent operational stage in pressure cells installed at the rock/lining interface.

Cores recovered in vertical boreholes drilled from the tunnel identified sheared discontinuities and the presence of tiny monoclinic crystals of gypsum, grown in the recent past.

These results reinforce the importance of damage in the development of expansion in Lilla tunnel, highlighted previously.

A simulation of the excavation of Lilla tunnel by means of a numerical thermo-hydro-mechanical and chemical FE model supported the generation of rock damage due to tunnel excavation and its important role in expansions. The model included the development of discontinuities and the description of the chemical processes of mineral dissolution and precipitation. It reproduced the generation of rock damage due to the tunnel excavation, and the development of gypsum crystallization. The calculated opening of fractures conditioned the occurrence of precipitation of gypsum in the fractures. The model reproduced the development of strains only within the upper 4-5 m thick active layer below the tunnel floor. Figure 8 shows the calculated opening of fractures due to the stress relief and the precipitation of gypsum at increasing times.

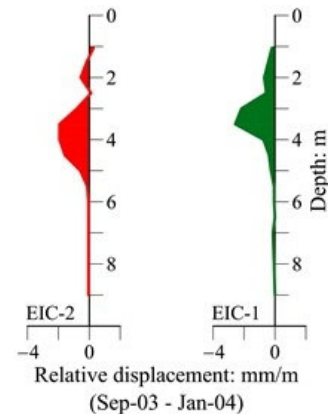


Figure 7. Sliding micrometer readings in a circular test section protected by a stiff lining.

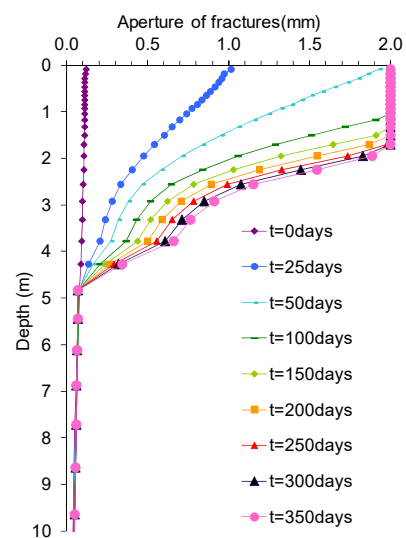


Figure 8. Variation with depth of calculated aperture of fractures below de flat slab at the axis of the tunnel.

## 5 HEAVE OF PONT DE CANDÍ VIADUCT

Pont de Candí bridge, is located in the vicinity of the North portal of Lilla tunnel. Each pillar of the viaduct is supported by a group of 9 bored piles, 1.65 m in diameter, and 20 m long on average. The four central pillars of the bridge are founded in a rigid stratum of anhydritic claystone formation, the same formation crossed by Lilla tunnel. A singular continuous heave was detected at the central pillars of the bridge after the end of construction (Alonso & Ramon, 2013). Figure 9 represents two heave profiles along the bridge that were recorded at the deck of the viaduct. The two central pillars of the bridge evolved at high rates ranging from 5 to 10 mm/month without stabilization.

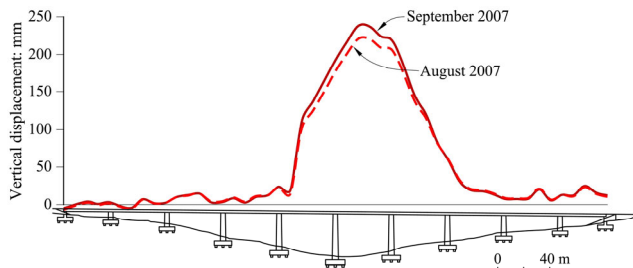


Figure 9. Heave recorded along the deck of Pont de Candí viaduct. Initial lecture: September 2002.

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 (Figure 10), at the positions where anhydrite is present in the rock. The presence of gypsum crystal growth was observed in some open discontinuities in the material recovered from depths corresponding to the active expanding layer. This observation explains that the swelling process is related with gypsum crystallization in fissures.

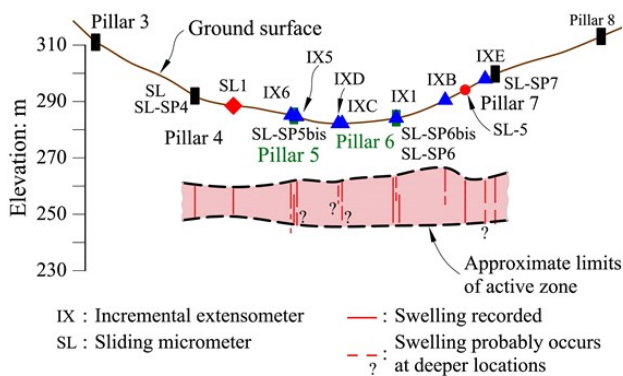


Figure 10. Location in depth of the active expanding layer below the central pillars of Pont de Candí bridge identified by sliding micrometers (SL) and incremental extensometers (IX).

The in-situ investigation carried out provided a relevant piece of information to understand the triggering conditions of expansions in the foundation material of Pont de Candí viaduct and the role played by rock damage in this case. As mentioned before, one necessary condition for the development of swelling in these materials is the presence of void space for the precipitation of gypsum crystals. However, no large excavation was performed in the site of the viaduct that could explain the development of rock damage.

Hydraulic cross-hole tests performed at different depths, along three boreholes, 50 m long, located near the central pillars of the bridge, brought valuable information in this regard. Cross-hole test results showed that a horizontal permeability,

several orders of magnitude higher than the expected value in a claystone, exist in the active expanding layer (Ramon & Alonso, 2013).

Figure 11 shows the layout of the cross-hole tests performed. Water was injected at a controlled depth inside one borehole, and water pressures were measured in other boreholes located in the close vicinity. A value of permeability about  $2 \cdot 10^{-6}$  m/s was found at depths corresponding to the active layer, and much lower values were obtained at deeper levels. The analysis of the results showed that the active expanding layer had a system of open horizontal discontinuities, that were hydraulically connected. No hydraulic connection was found in vertical direction.

In Pont de Candí viaduct site there is no construction-related stress relief in the rock mass. However, the rock damage was already present in the rock mass before the viaduct construction. The existing open fractures explain the measured high permeability and the availability of “open” space required to host the development of precipitation of gypsum crystals. In this case the water needed to initiate the precipitation of gypsum was supplied by a shallow aquifer, connected with the deeper anhydritic claystone by a high number of investigation borings and monitoring devices. Probably the large diameter excavated piles played the same role. This is, again, a case of a damaged rock at the origin of heave. Unlike the previous two cases the viaduct construction supplied, indirectly, the necessary downward water flow towards the fractured rock.

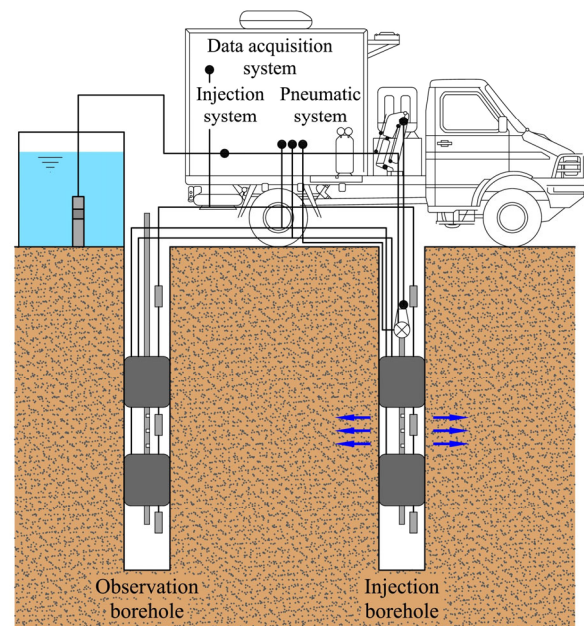


Figure 11. Layout of the cross-hole hydraulic tests performed.

## 6 CONCLUSIONS

The paper highlights the importance of the damage in the rock for the development of expansions induced by gypsum crystal growth in anhydritic formations. The concept of damage in the context of this paper is associated with the generation of volume (pore space, fractures, discontinuities) and their spatial connections. There is a limiting restriction for the nucleation and growth of gypsum crystals based on the size of pores. This means that crystals will not precipitate if there is not enough available “free” space for their precipitation. Published studies indicate that the precipitation of crystals will be difficult to

occur in pores smaller than some tens of microns. The paper has focused on the importance of the available open space in the rock for the precipitation of gypsum crystals. Classical nucleation theory and studies on gypsum crystal precipitation indicate that the nanometric porosity of rocks prevent the precipitation of gypsum. Gypsum precipitation is favored in the fissures because they provide the necessary open space.

Expansions in anhydritic formations reported in the literature refer always to locations that involve tunneling, excavations or engineering works. No spontaneous significant swelling deformations have been detected in nature when no engineering works are involved. The evidence raised from the observation of real cases affected with anhydritic-expansions is that the construction works modify the natural conditions of the rock mass and provides the triggering of rock expansion. In addition, the analysis of the real cases presented here demonstrate that the development of gypsum crystal induced expansions requires a damaged rock. Otherwise expansion doesn't exist.

The large excavations performed during the construction of the Nuclear Power Station (NPS) and Lilla tunnel, damaged the rock mass due to the stress relief. In addition, the use of blasting during the excavations intensified the rock damage. The heave phenomena occurred only at the damaged zones. For instance, in the NPS, piezometric data provided evidence of a set of open fissures in the active layer of the foundation claystone identified by the extensometers. Monitoring records in both cases show that the active layers had fixed dimensions over time, without evolving to deeper positions. This observation indicates that the precipitation of gypsum only occurs in fractures with a certain opening.

The rock damage necessary to provide enough space for crystal precipitation can also exist in the rock mass due to a previous geological phenomenon. This is the case in Pont de Candí viaduct heave. The fractured anhydritic claystone was identified in survey borings and hydraulic tests to determine the rock permeability.

## 7 ACKNOWLEDGEMENTS

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