Analysis of ettringite attack to stabilized railway bases and embankments

Analyse de l'attaque chimique par ettringite de remblais et plateformes ferroviaires stabilisées

Ramon A.
Department of Geotechnical Engineering and Geosciences, UPC, Barcelona, Spain
International Center for Numerical Methods in Engineering (CIMNE), UPC, Spain
Alonso E.E.
Department of Geotechnical Engineering and Geosciences, UPC, Barcelona, Spain

ABSTRACT: Two cases of massive sulphate attack to cement treated embankments and track bases in a high speed railway line are described. In the first case, two large access embankments to a railway viaduct were treated with jet–grouting columns. In the second case a compacted cement treated soil was placed over a rigid concrete caisson. The treated layer, 1.5 m thick, expanded at a continuous rate of 0.9-1.3 mm/month. In the two cases the soil was excavated from nearby cuts in gypsiferous Tertiary (Oligocene) claystones. Ettringite and thaumasite crystals were found within the expanding levels. The chemical evolution of an interface between a cement treated body and a compacted soil is presented. Solutions adopted to remediate the created problem are briefly described.

RÉSUMÉ : On décrit dans cet article deux cas d'attaque par sulfates, la première dans un remblai traité au ciment et la deuxième dans une plateforme ferroviaire de train à grande vitesse. Plus précisément, le premier cas traite de deux grands remblais d'accès à un viaduc de chemin de fer qui avaient été stabilisé avec des colonnes de jet-grouting. Le second cas considère une couche de sol compacté traitée au ciment et reposant sur des caissons rigide en béton. Dans les deux cas, le sol était le matériau provenait d'excavations proches dans des argilites tertiaires (Oligocène) gypsifères. La couche traitée 1,5 m d'épaisseur a gonflé à un taux continu de 0.9 à 1.3 mm / mois. Des cristaux d'ettringite et thaumasite ont été trouvés dans les niveaux gonflants. L'article présente l'évolution chimique qui se produit à l'interface entre un corps traité au ciment et un sol compacté. Les solutions adoptées pour remédier au problème sont brièvement décrites.

KEYWORDS: Swelling, ettringite, gypsum, sulphate attack, embankments

1 INTRODUCTION

Sulphate attack in cement and lime treated soils has been often reported in stabilised road bases and subbases when the soil has some proportion of gypsum, or the treated soil is exposed to sulphated waters. Sulphate attack results in loss of strength and significant heave (Sherwood, 1962; Mitchell & Dermatas, 1992; Puppala et al., 2003; Rajasekaran, 2005). Some of these studies discuss the minimum sulphate content which triggers the attack. Sherwood (1962) described an unconfined compressive strength reduction of 24% of treated soil when the sulphate content was as low as 0.25%.

Sulphate attack leads to the development of ettringite ($Ca_6[Al(OH)_6]_2(SO_4)_3\cdot 26H_2O$). This mineral crystallises in bundles of elongated filaments. The development of ettringite implies a destruction of the strength of the cement paste and a substantial swelling. Another mineral, thaumasite ($Ca_6[Si(OH)_6]_2(CO_3)_2(SO_4)_2\cdot 24H_2O$), develops also as a consequence of sulphate attack. In both minerals, the presence of water is remarkable. The development of ettringite and thaumasite follows a complex process which has been described by Mitchell & Dermatas (1992) and Mohamed (2000). The highly basic environment (pH in excess of 12) created by the hydration of cement's calcium oxide is capable of dissolving the clay minerals and releasing Al and Si ions. High pH also favors the dissolution of sulphate minerals, which provides Ca^{++} and SO_4^{--} ions. Ettringite precipitates when aluminum released from clays, calcium from cement or lime and sulphates combine with water molecules. Carbonic acid, present in the pore water and the dissolution of calcite leads to precipitation of thaumasite, once ettringite is present. Crystals develop in the pore solution.

Most of the geotechnical literature on sulphate attack concerns the stabilisation of compacted road bases and subbases. In those cases the treatment is applied to relatively thin layers and the sulphate attack results in surface heave and reduction of soil strength. In contrast, the two cases affected by sulphate attack described here concern larger soil masses in railway embankments. Field observations, laboratory tests and remedial measures are described below.

2 PALLARESSOS EMBANKMENTS

Thaumasite and ettringite crystal growth is at the origin of an intense expansion that affected two embankments, 18 meters high, located in the Madrid-Barcelona high speed railway. The case of sulphate attack to Pallaressos embankments is described in detail in Alonso and Ramon (2012).

The embankments were made of compacted sulphated Tertiary claystone. The embankments material belongs to the same geologic formation where Lilla tunnel (Alonso et at., 2012) and Pont de Candí bridge (Alonso and Ramon, 2012), have experienced severe heave problems due to gypsum crystal growth.

Pallaressos embankments give access to a bridge 196 meters long. A transition wedge was built next to abutment structures in both embankments in order to provide a progressive change of stiffness when trains approach the rigid bridge structure. Cement treated soil was used for the construction of both wedges (Figure 1).

Heave of the surface of embankments, near the abutments, was detected at an early time after the end of the embankments construction during the track levelling monitoring carried out periodically by the railway administration. Afterwards a grid of jet grouting columns was executed on both embankments to stabilize the embankment material. However, heave rate did not stop after the jet grouting treatment. Continuous extensometers installed in boreholes through the embankments showed that strains were developing in the upper 8-10 m of the embankments (Figure 2).

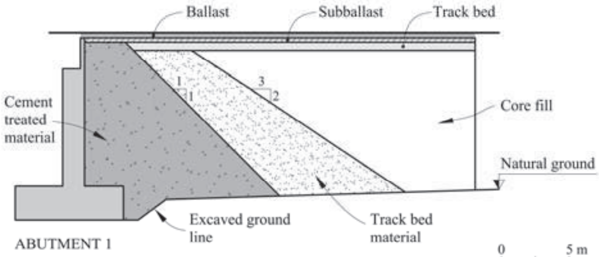


Figure 1. Design of the embankment

Inclinometers installed in boreholes indicated that swelling deformations occur not only in the vertical direction, but also in the horizontal direction. Monitoring of topographic marks installed on the surface of the embankments confirmed that a volumetric swelling was deforming the embankments. The distribution of displacements along the embankment axis agrees with the intensity of the jet-grouting treatment.

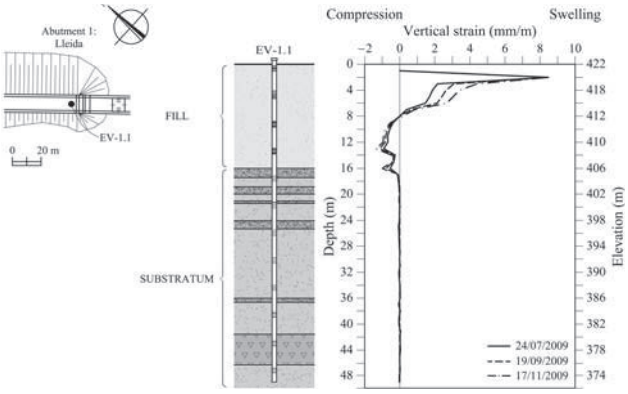


Figure 2. Vertical strains measured by sliding micrometer EV-1.1

Ettringite and thaumasite crystals were found in all the samples of embankment material, recovered from boreholes, that were analyzed by means of X-ray diffraction (XRD) and scanning electron microscope with an energy dispersive spectrometer (SEM-EDS) (Fig. 3). The combination of sulphates from the soil, alumina and silica released from clay minerals because of the alkaline environment, calcium from cement components, present in the transition wedges and in the jet-grouting treatment, and also from gypsum, carbonates released from calcite and the availability of water from rainfall leads to the formation of ettringite and thaumasite. The formation of thaumasite and ettringite is essentially unlimited because of the availability of the necessary components for its formation in the embankments. It was concluded that deformations in the embankments will proceed for a long time if no remedial measures were carried out.

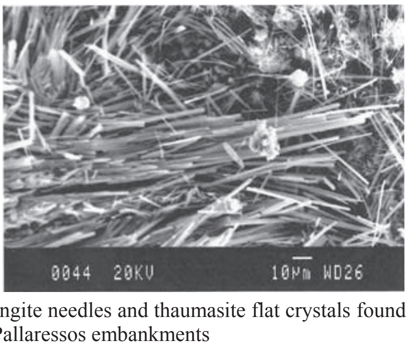


Figure 3. Ettringite needles and thaumasite flat crystals found in a tested sample from Pallaressos embankments

A finite element model of embankment swelling was developed to calculate the swelling loads against the bridge abutments and also to estimate the state of stress on the embankments (Alonso and Ramon, 2012). It was found 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.

3 SOIL TREATMENT OVER UNDERPASS

3.1 *Introduction*

The second case concerns a rigid reinforced concrete caisson structure 11.2 m wide and 6.25 m high, built under the railway tracks to allow for the crossing of an aqueduct. The structure was capped by a layer of cement treated soil, 1.5 m thick.

Above, base and ballast layers complete the layered system supporting the railway tracks. Figure 4 shows a cross section of the caisson. Material for the fill came from a nearby cut in the same railway line. The exposed slopes showed the soil formation: a Tertiary red claystone with abundant gypsum veins.

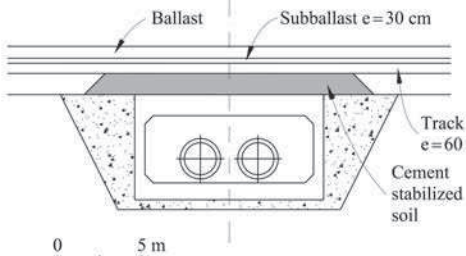


Figure 4. Cross section of the caisson of the underpass.

Periodic track levelling detected a progressive heave of the tracks above the caisson. The maximum accumulated vertical displacement measured in July 2011 was about 12 cm.

3.2 *Field data*

Topographic levelling of the caisson didn’t show any vertical displacement of the structure. This indicated that the vertical displacements measured at the rail tracks were a result of the behaviour of the material placed above the concrete caisson. A convex surface, centred in the caisson axis, was also visible in the field (Figure 5). In addition, the thickness of the ballast layer was noticeably lower in the bulging area, because of the necessary periodic ballast thickness correction. Two high precision (± 0.003 mm/m) vertical continuous extensometers (SL-1 and SL-2), 10 m long, were installed in boreholes located in the caisson backfill material, close to the concrete structure. Both extensometers recorded the development of vertical strains at both backfills within the upper 4 m (Figure 6 and Figure 7). A maximum heave rate of 1.33 mm/month was measured between 17th, February 2012 and 19th, April 2012. A heave rate of 0.91 mm/month was recorded during the same period at the same depths in the other backfill (SL-2).

Continuous cores and undisturbed samples were recovered from boreholes performed for the installation of extensometers. A few SPT tests were also performed in borings SL-1 and SL-2 at depths of 0.6-2.50 m. The recorded values (N = 46, 25, 39, 26, 42) reveal a compact material although the presence of gravels complicate the interpretation. A borehole 2.8 m long was also drilled above the caisson, centred along the axis of the caisson. A value N = 20 was measured in this location at a depth of 1.30-1.90 m. Interestingly, the material recovered from boreholes at depths varying from 1.2 to 2.75 m was found to be soft and wet or very wet. At those depths the existence of a heavily weathered material with presence of a mixture of cement and some sand was also observed.

Figure 5. Bulge of the surface above the caisson. Observe the reduced thickness of the ballast layer

3.3 *Laboratory tests*

A mineralogical analysis by means of X-ray diffraction on samples recovered from the upper meters of boreholes revealed the presence of ettringite and gypsum in the material recovered from the treated (classified as low plasticity clay and sand mixtures).Calcite, quartz, dolomite and illite were also found. The presence of wet material can be probably related with the ettringite crystal growth because the crystalline structure of ettringite crystals content a high percentage of water.

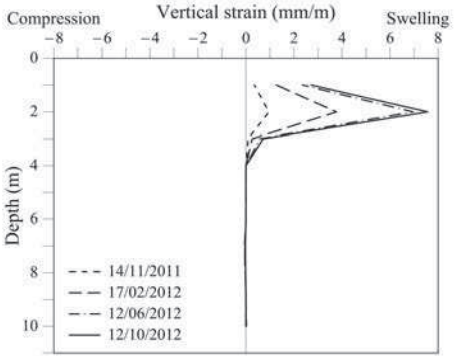


Figure 6. Vertical strains measured in depth along the continuous extensometer SL-1 installed within the backfill of the concrete caisson

Identification tests were performed on samples recovered from boreholes drilled at the backfills and above the caisson. Sulphate and soluble salts content tests were also conducted on some of the recovered samples. The soluble sulphate content obtained in all samples is lower than 1%. The water contents in the samples tested from boreholes SL-1 and SL-2 are respectively 8.4% and 11%. A maximum value of water content of 16.1% was measured in the laboratory in a sample recovered from the layer placed above the caisson. The values of dry density and water content in the tested samples indicate that the materials located in the upper layers in the vicinity of the caisson not only have increased in humidity but they had also lost density. The increase in humidity and the decrease in density are related to the crystal growth associated with the sulphate attack to cement.

Free swelling tests were performed on samples prepared with the material recovered in boreholes. Undisturbed samples as well as samples compacted at the dry density corresponding to the Normal Proctor test were tested. All samples were partially submerged in water and were placed inside a cold-storage chamber at a constant temperature of 8ºC during the test to reproduce favourable conditions for ettringite and thaumasite growth. Two types of samples were tested with material from each location. Figure 8 shows the vertical swelling strains measured during the free swelling tests performed. Swelling evolves in time in all the samples tested without signs of levelling off.

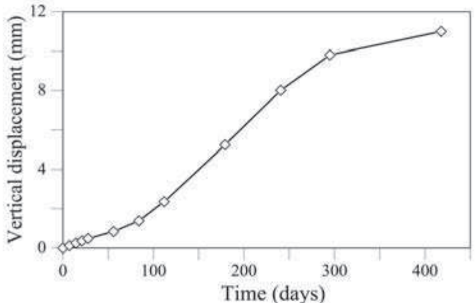


Figure 7. Accumulated vertical displacements measured by a continuous extensometer

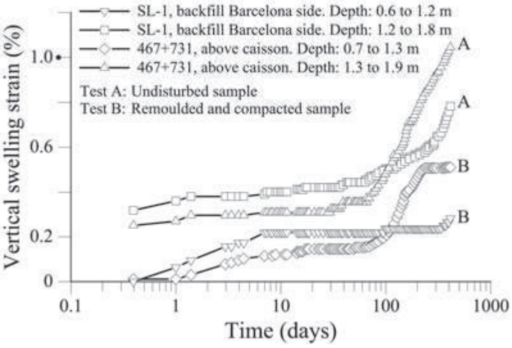


Figure 8. Swelling vertical strains recorded in free swelling tests

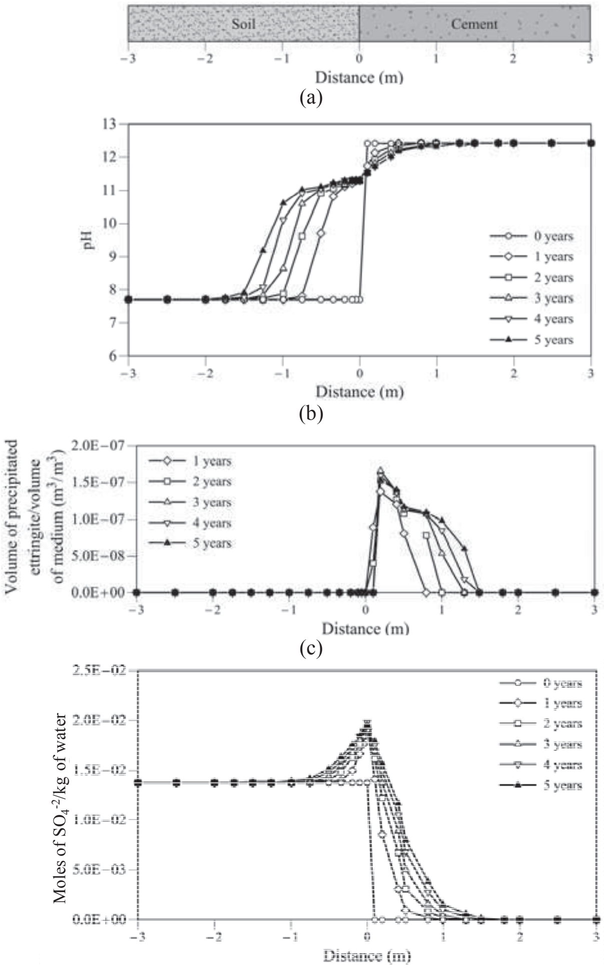
4 CHEMICAL MODELLING

With the purpose of getting an improved understanding of the sulphate attack, a simulation of the processes taking place at the soil-cement interface was performed with the help of a general purpose transport and chemical reactions program (RETRASO: Reactive Transport of Solutes: Saaltink et al., 2005). RETRASO solves the coupled hydraulic transport processes and the chemical reactions. The code handles mineral precipitation and dissolution reaction under a large set of experimental kinetic and equilibrium laws.

A simple 1-D problem, illustrated in Figure 9a, was analyzed. Two porous materials, the compacted soil and a cement grout, interact through a common interface. Only diffuse processes are considered. There was an interest in knowing the evolution and distribution of constituents in space (on both sides of the interface) and time, and the pH of the medium, a key piece of information to explain the sulphate attack. This geometry is especially relevant for the attack of jet grouting columns in Pallaressos embankments.

Initial equilibrium values, pH = 7.7 and pH = 12.4, were calculated for aqueous solutions in equilibrium with soil and cement, respectively. Then, RETRASO was used to obtain the precipitated or dissolved amounts of calcite, dolomite, gypsum, ettringite, kaolinite, quartz and portlandite (calcium hydroxide). Some results are given in Figure 9 for a calculation period of five years.

The pH maintains a high value on the cement side of the interface. A plume of high pH values migrates progressively towards the soil (Fig. 9b). In parallel, an ettringite front advances (Fig. 9c) in the cement medium. In 5 years, a deep penetration is calculated (~ 1.5 m). The sulphate attack started (against the treated wedge and, later, against jet grouting columns) in 2006 soon after the end of the embankment construction. The calculated depth of the ettringite front in Figure 9c suggests that the attack has currently (2012) affected the whole volume of the grouted columns. In fact, in all samples from embankments recovered at different positions, ettringite and/or thaumasite was identified. Kaolinite is being progressively dissolved in the soil, starting at the interface.



(a) (b) (c) (d)

Figure 9. Analysis of the soil-cement reactions with the program RETRASO. (a) Geometry of the problem; (b) Evolution and distribution of pH; (c) Volumes of ettringite and (d) Concentration of sulphate.

The consequence is the release of Al ions, necessary for ettringite precipitation. The concentration of sulphate increases at the interface and immediate vicinity (Fig 9d), which induces the precipitation of ettringite.

Even if the analysis performed is quantitative, the calculated volume fraction of precipitates (or dissolved species) is not believed to be representative. The real problem is exceedingly complex: the reactive surface is unknown (a small value, 0.14 m^2/m^3, was adopted in the calculation model), there are uncertainties on the validity of the kinetic equations, the pore water was probably under significant suction values for most of the time, initial volume fractions and diffusion coefficients were estimated, etc. Therefore, no attempt was made to couple the chemical calculations with the observed heave. Nevertheless, the chemical analysis performed provided a good understanding of sulphate attack.

5 CONCLUDING REMARKS

The field swelling records suggested that heave of the treated embankments and above the caisson could continue for years at a sustained rate. Modifying the thickness of the ballast cushion below the rail tracks could not cope with the expected medium term heave. Forces against the abutment wall in the case of the embankment were damaging the bridge and a passive state of stress, menacing the rail tracks, had developed in the upper part of embankments.

It was then decided to excavate the upper 6 m of the embankments in the stretch affected by sulphate attack. Also, it was decided to support rail tracks by a structure founded on piles on both sides of the embankment. Supporting piles (excavated piles which reach the substratum) were first built. Once the rail tracks were underpinned, the upper part of the embankments was excavated in stretches and reinforced concrete slabs were slid in place. An open gap, 3 m thick, was left between the lower surface of the slabs and the new upper surface of the embankments.

The solution of the heave problem above the caisson requires the removal of the cement treated layer and its substitution by a stable compacted granular material. This operation will not impair the circulation of trains.

6 ACKNOWLEDGEMENTS

The authors acknowledge with thanks the technical and economic support provided by ADIF (National Agency for Railway Infrastructure). Thanks are also given to contractors and IIC, for their contribution to the identification and characterization of the geotechnical conditions of the material, and to professors E. Vázquez, Dr. M. Barrera and E. Tauler for their contribution in the identification of minerals.

7 REFERENCES

Alonso, E. and Ramon, A. (2012). Massive attack to cement treated railway embankments made of compacted sulphated clay. Géotechnique, in print.

Alonso, E. E. and Ramon, A. (2012). Heave of a railway bridge induced by gypsum crystal growth. Field observations. Printed online in Géotechnique.

Alonso, E.E., Berdugo, I.R. and Ramon, A. (2012). Extreme expansive phenomena in anhydritic-gypsiferous claystones: the case of Lilla tunnel. Géotechnique, in print.

Mitchell, J.K. & Dermatas, D. (1992). Clay soil heave caused by lime-sulphate reactions, *ASTM Special Technical Publication,* **1135**, 41–64.

Mohamed, A. M. O., 2000. The role of clay minerals in marly soils on its stability. *Engineering Geology* **57**, 193-203.

Puppala, A.J., Wattanasanticharoen, E. & Punthutaecha, K. (2003). Experimental evaluations of stabilisation methods for sulphate-rich expansive soils. *Ground Improvement*, **7**, No.1, 25–35.

Rajasekaran, G., (2005). Sulphate attack and ettringite formation in the lime and cement stabilized marine clays. *Ocean Engineering*, **32**, 1133–1159.

Saaltink, M., I., Ayora, C. & Olivella, S. (2005). *User's guide for RetrasoCodeBright (RCB)*. Departament of Geotechnical Engineering and Geo-Sciences, Technical University of Catalonia. Institute of Earth Sciences Jauma Almera, Spanish Research Council (CSIC), Barcelona. 111 p.

Sherwood, P.T. (1962). Effect of sulphates on cement and lime stabilized soils. *HRB Bull.,* **353**, 98–107.