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On the swelling behaviour of weak rocks due to gypsum crystallization

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Abstract

The paper describes the case of an industrial pavement in Northern Italy, subjected to significant uplift (up to 0.2-0.4 m) due to the response of the rock mass below the concrete floor. The study included monitoring the pavement for a long period of time, the execution of a geotechnical investigation campaign and a number of X-ray diffraction analyses. The results of the investigation suggested that a strong correlation exists between the uplift of the pavement, the swelling behaviour of the material exposed by the excavation and the chemical process of gypsum crystallization.

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Keywords: swelling; argillite; anhydrite; gypsum; crystallization

1. Introduction

The design of engineering structures interacting with rock masses needs to take into account the potential deformational behaviour of the rock mass under the induced state of stress. For most rock types various constitutive models can be used with confidence as long as there is no interaction between the rock-forming minerals and water.

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However, if water chemically interacts with the rock minerals the behaviour of the rock mass becomes more difficult to predict [1].

The swelling behaviour of sedimentary rocks has been extensively studied by many researchers and is generally most evident in deep underground excavations, such as tunnels and underground mining [2,3]. On the contrary, there are limited documented cases in the literature referring to shallow formations. In argillitic rocks, hydration of anhydrite ($CaSO_4$) and dehydration of gypsum ($CaSO_4 \cdot 2H_2O$) lead to alternating volume changes, posing serious engineering problems to human structures. Anhydrite in surface layers readily imbibes any available water and quickly converts into gypsum. The associated swelling is known to create pressure on the walls and heave in the floors of tunnels as well as uplift of foundations. As an example, the Vobarno tunnel in Italy, not far away from the site of the case study presented in this paper, was constructed through anhydrite and gypsum formations. Completed in 1931, it gave no trouble until 1940 when it suddenly began to crack and progressively heave, causing the concrete lining to disintegrate into rubble [4].

The paper presents a case study regarding an industrial pavement constructed in 2000 in Lumezzane (Brescia, Northern Italy), subjected to significant uplift (up to 0.2-0.4 m) between 2003 and 2008, due to the swelling of the foundation material. The study was conducted with a multidisciplinary approach that included either monitoring the pavement for a long period of time, or the execution of geotechnical investigations in situ and laboratory testing, and X-ray diffraction analyses to assess the mineralogical composition of the foundation materials.

2. Geochemical and engineering aspects of anhydrite/gypsum phase transition

Mineral transition between anhydrite ($CaSO_4$) and gypsum ($CaSO_4 \cdot 2H_2O$) takes place according to the following reversible hydration-dehydration reaction (1):

$$CaSO_4 + 2 \cdot H_2O \leftrightarrow CaSO_4 \cdot 2H_2O \tag{1}$$

Aside from the chemistry of the water, the chemical relation (1) is governed by temperature and pressure [1,5,6]. The hydration-dehydration reaction alters the crystalline structure of the resulting mineral; therefore estimates of volume changes associated with such mineral transition should be based on the molar volumes of gypsum, anhydrite and water [5]. Table 1 summarizes the theoretical assessments on the volume changes due to hydration and dehydration of calcium sulphate minerals for “open” and “closed” systems [1]. Open systems allow free exit/entry of water during hydration/dehydration, whereas a closed system is defined as an environment where water is trapped with the calcium sulphate minerals before and after the transition. In open systems, gypsification is associated with a volume increase of up to 63%, whereas dehydration of gypsum results in a volume decrease of up to 39%. The volume changes for closed systems take place in the opposite direction, so that anhydrite hydration results in a volume decrease of 9% and gypsum dehydration results in a volume increase of about 10% [5]. It must be noted that the above estimated volume changes are intended for complete mineral transition and provide the boundary values for hypothetical situations. Actual volume changes in the field are governed by many factors such as the in situ porosity, the homogeneity of composition and the nature of the system (the characteristics of the rock mass, the water regime). Volume change predictions for systems with partial water access and incomplete mineral transition are complex and, although they would fall between the boundary values, direct measurements are necessary to determine the engineering behaviour of local formations [5].

Table 1. Theoretical maximum volume changes in calcium sulphate minerals [1,5]

Volume	Open system		Closed system	
	hydration	dehydration	hydration	dehydration
Initial [cm^3]	$V_A = 45.9$	$V_G = 74.7$	$V_A+2V_L = 45.9+36.2$	$V_G = 74.7$
Final [cm^3]	$V_G = 74.7$	$V_A = 45.9$	$V_G = 74.7$	$V_A+2V_L = 45.9+36.2$
Change [(Final/Initial – 1)×100]	+62.8	-38.6	-9.0	+9.9

3. The case study

A new industrial area was constructed in 2000 near Lumezzane (Province of Brescia, Northern Italy). The site is located on a hillslope of the Prealps chain, at an elevation of approximately 500 m above sea level and has been obtained from the excavation (up to 15 m deep) of a large hilly area (500 m x 170 m). Figure 1 shows the site plan view and a portion of cross section of the excavated profile. The plan view highlights the presence of a number of creeks hosting occasional streams of water that were diverted and buried before the construction of the industrial utilities. Before construction, in 1995 and in 1998, two geotechnical investigation campaigns were carried out (before the authors' involvement), consisting of borings and geophysical tests, by means of the seismic refraction method (the location of borings and geophysical tests is reported in Figure 1a). The excavation for the new industrial area was almost entirely conducted in the geological formation of Riva di Solto (Fig. 2), named after the not-far-away village in the Province of Bergamo. It consists of argillite and marly argillite, that originated in the Raethian (Upper Triassic, 201-208 Ma), sometimes rich in organic matter, black in colour. Starting from 2003, some portions of the industrial concrete floor within the newly constructed buildings began to rise and crack. The early measurements are very limited and poorly distributed in time. However, since there was no movement near the piled footings or in areas where the heavy industrial equipment was installed, it was possible to estimate a cumulated uplift of the floor in the range of 0.05-0.40 m. Figure 3 shows selected measurements of floor uplift recorded for a few months in the points A and B of building A1 (located in easternmost portion of the site). The last measurements were integrated with the records of the weather conditions (merely indicating the occurrence of rain) and demonstrated almost immediate uplift phenomena in response to increase in humidity due to the local precipitations (i.e. uplift measurement peaks on rainy days recorded between September and November 2008).

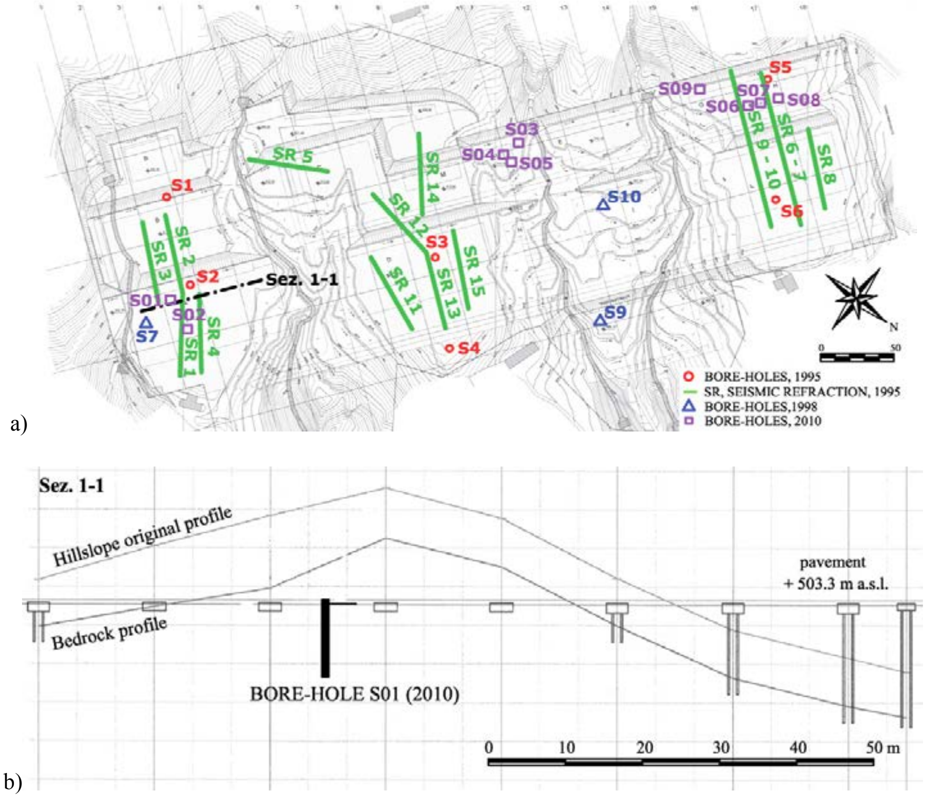

Fig. 1. a) Plan view of the construction site after the excavation stage and location of bore-holes and geophysical tests; b) Cross section 1-1 with indication of the hillslope original profile, the bedrock profile and the foundation scheme of Building A1.

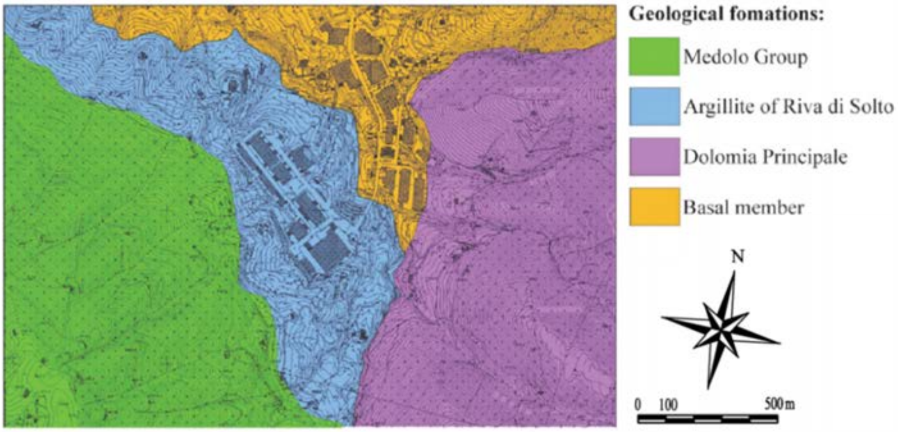

Fig. 2. Simplified distribution of the main geological formations in the area of the construction site [7].

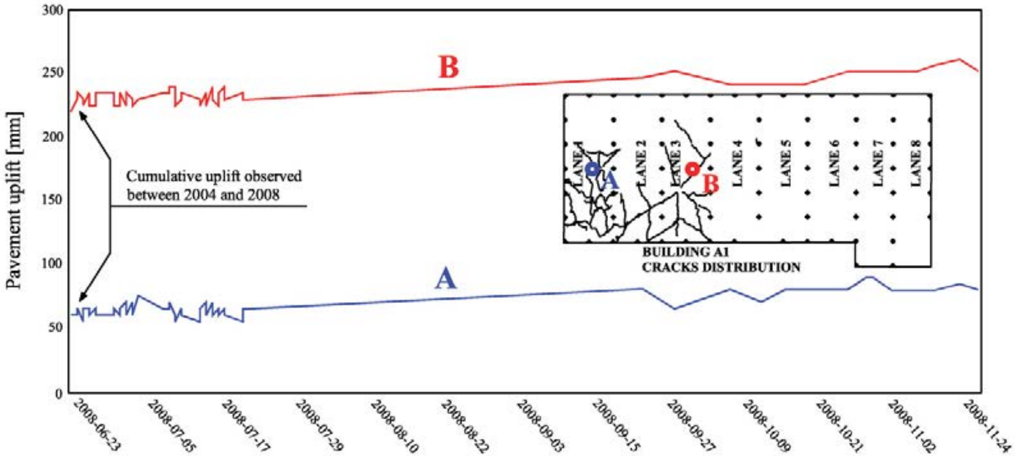

Fig. 3. Uplift measurements of the concrete pavement in Building A1 (see cross section 1-1 in Fig. 1b); schematic cracks distribution in the inset.

4. Multidisciplinary investigation campaign

Upon the authors' involvement (2010), a new, multidisciplinary investigation was promoted to analyse the observed phenomena. The experimental campaign included extensive mapping of the raised flooring to identify areas characterized with the most significant heave, and a new series of 9 borings (rotary drilling, without circulation of water), organized in couples, i.e. located in the most swelled areas (S01, S04, S06, S07 in Figure 1a) and in nearby locations where the swelling did not occur (S02, S03, S05, S08, S09 in Figure 1a).

The obtained samples were subjected to traditional geotechnical/geomechanical testing that comprised swelling tests according to ASTM D4546-14 [8]. Finally, to investigate the nature of the material at the micro-scale and to identify a possible correlation between the mineralogical composition and the response to a change in humidity of the volume element, a large number of X-ray diffraction analyses (XRD) were carried out on samples obtained from the borings drilled in the swelled areas and from those in the nearby non-swelled zones, at given depths. XRD analyses were conducted with a Philips PW-1820 diffractometer; diffraction spectra were collected in the range 3-60° with 0.03 2-theta steps and 2 s/step counting time. The resulting spectra were initially qualitatively studied by means of searchmatch programs and later analyzed according to the Rietveld method [9]. The mapping of the industrial site (Fig. 1, Fig. 3 inset) indicated that the portions of raised flooring were located in areas of deep excavation not subjected to loads by the building structures and by the heavy industrial equipment. The distribution of vertical movements, however, was not uniquely related to the unloading pattern produced by the excavation of the original site. The mentioned series of 9 boreholes (up to 10 m deep) were therefore aimed at identifying possible discrepancies between swelled and non-swelled areas. The samples were subjected to traditional classification tests and swelling tests, but neither could provide a clue on the reason for the discrepancy in the observed behavior. For instance, the laboratory tests performed to measure the response of rock samples to a change in humidity have shown a modest swelling behavior, probably due to the fact that the swelling potential was already entirely exploited on site (Fig. 3).

XRD analyses were then executed on samples taken from the concrete floor, from the backfill underneath the pavement and from the intact bedrock below. The analyses conducted on the backfill (whose thickness in the center of the excavated area is approximately 0.3 m), indicated the presence of dolomite (predominant), calcite, quartz and gypsum (only in traces). The results of tests performed on samples of intact bedrock (formation of Riva di Solto) indicated the presence of two types of mineralogical compositions:

1) predominantly argillitic, with fractions of illite, kaolinite, quartz, calcite, pyrite, and traces of complex clay minerals (smectite, montmorillonite, halloysite);

2) predominantly limestone/marl composition, with calcite (predominant), quartz and traces of clay minerals and pyrite.

The samples with a predominantly argillitic composition (retrieved from the uppermost logs of bore-holes S01, S04, S06 and S07) indicated the presence of significant fractions of gypsum (6-14%). Instead, the same mineral was detected only in traces (0.1-1.0%) in samples taken from the companion bore-holes, drilled in areas where the swelling did not occur. Figure 4 shows X-ray diffraction patterns of two selected samples at surface (green) and at 3 m depth (brown) respectively. The indicative gypsum peak is visible at 11.5 2-theta angle. The diffraction peaks of chlorite, illite and quartz are labelled in the inset figure. Table 2 presents a comparison in terms of mineralogical composition (derived from the analyses of XRD tests) of samples taken from bore-hole S01 and from the companion S02 (results are limited to a depth of 3 m below ground level, location is reported in Figure 1), revealing the mentioned presence of gypsum at shallow levels of borehole S01 only.

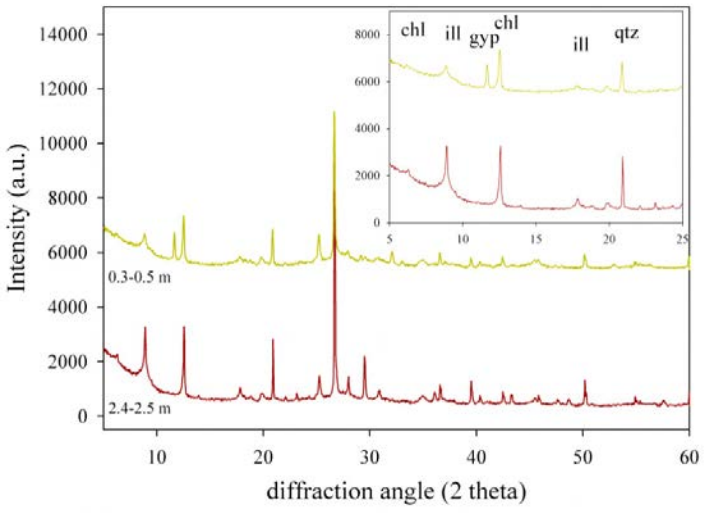

Fig. 4. X-ray diffraction patterns of selected samples.

Table 2. Mineralogical composition of samples obtained from bore-holes S01 and S02 (2010).

Boring-sample ID (-)	Depth (m b.g.l.)	Calcite	Dolomite	Illite	Gypsum (%)	Kaolinite	Quartz	Pyrite
S01-02	0.3-0.4	4.9	87.2	3.9	0.9	0.2	2.9	0.0
S01-03	0.8-0.9	24.8	0.0	35.2	10.8	2.5	25.3	1.4
S01-04	1.2-1.3	46.6	0.0	7.2	13.9	3.4	26.6	2.3
S01-05	1.5-1.6	36.7	0.0	19.9	12.3	2.9	25.3	2.9
S01-06	1.9-2.0	9.7	48.8	17.1	0.8	3.3	20.3	0.0
S01-07	2.4-2.5	38.6	1.6	28.3	0.5	5.4	22.9	2.7
S01-08	2.9-3.0	72.2	2.5	11.1	0.3	2.1	10.3	1.5
S02-02	0.2-0.4	16.9	49.7	18.5	0.6	2.0	12.2	0.1
S02-03	0.4-0.5	13.2	56.5	15.9	0.7	1.7	11.7	0.3
S02-04	0.8-0.9	11.1	1.9	40.5	0.1	12.6	32.7	1.1
S02-05	1.4-1.5	31.3	2.4	28.3	0.1	10.9	26.3	0.7
S02-06	1.9-2.0	7.7	4.3	38.3	0.1	13.0	35.8	0.8
S02-07	2.4-2.5	36.8	1.6	23.0	1.7	10.9	25.3	0.7
S02-08	2.9-3.0	1.0	53.3	19.8	1.6	9.8	13.9	0.6

5. Conclusions

A case study of a pavement subjected to significant uplift was analysed with a multidisciplinary approach to investigate the nature of the foundation material at the micro-scale and identify a possible correlation between the mineralogical composition of the rock and the swelling response of the volume element. The result of XRD analyses indicated the presence of gypsum in the uppermost layers of the bedrock underneath the swelled areas of the pavement. The results of the investigation suggested that a strong correlation exists between the uplift of the pavement and the swelling behavior of the material exposed by the excavation, associated with the crystallization of gypsum, combined with the new state of stress and the change in humidity generated by the construction.

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