Subsidence hazards connected to quarrying activities in a karst area: the case of the Moncalvo sinkhole event (Piedmont, NW Italy)

Sabrina Bonetto[a], Adriano Fiorucci[b], Mauro Fornaro[a], and Bartolomeo Vigna[b]

[a] University of Torino, 35 via Valperga Caluso, 10125 Torino, Italy; sabrina.bonetto@unito.it, mauro.fornaro@unito.it
[b] Politecnico di Torino, 24 C. so Duca degli Abruzzi, 10129 Torino, Italy; adriano.fiorucci@polito.it, bartolomeo.vigna@polito.it

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Abstract. Gypsum is an important raw material for constructions and other industrial sectors. In Piedmont (NW Italy), main gypsum bodies are located in the Monferrato area, where large open pits and underground quarries are present. The gypsum-bearing formation outcropping in this area shows typical geological, structural, and hydrogeological features, which affect the quarrying and the related interaction with natural phenomena, human activities, and land use. In particular, gypsum karst has considerable influence on mining operations, as well as mining operations can produce strong impact on gypsum karst. In Monferrato, a specific case of interaction between the quarrying activity and geological, hydrogeological, and territorial setting is represented by the event of water inrush that happened in the Moncalvo underground quarry in association with the development of a surface sinkhole phenomenon.

Key words: gypsum, quarries, karst, inrush, sinkhole, NW Italy.

INTRODUCTION

Quarrying activity has increased in the last few years due to the high demand for natural raw materials in different industrial sectors. An inadequate management of the exploitation of natural resources has frequently been responsible for environmental and safety problems. According to both the geomechanical behaviour of the material and the geohydrological features of deposits and vulnerability of the exploited sites, proper planning schemes and management are necessary in order to ensure the adequate use of raw materials and meeting the criteria of the environmental sustainability and safety of quarrying.

This study focuses on gypsum, which is an important raw material particularly for the industrial buildings sector. Because of its wide distribution, gypsum has been used for thousands of years in many geographical areas of the world: as building material (in Knossos Palace in Crete), dimensional stone (in Muslim Architecture), raw material to produce mortars (in Cheops Pyramid and stone ships), decoration plasters and base for polychrome paintings (in Nefertari Tomb), Gypsum exploitation has grown in the last few years due to the high demand on the domestic and international market and new quarries have been opened (Bonetto et al. 2005; Bonetto 2006). However, some problems should be considered in gypsum quarries, related to karst phenomena, water circulation, and geomechanical features, which influence mining activities. The investigated area corresponds to the Monferrato domain (Piedmont, NW Italy), belonging to the Tertiary Piedmont Basin, where all active gypsum quarries of Piedmont are located (Fig. 1).

METHODS OF GYPSUM EXPLOITATION AND MINING TECHNOLOGIES

According to the local geological, structural, and morphological setting, the exploitation activity is nowadays set up in open pit and underground hillside quarries. Open pit quarrying is applied if burdens have a relatively small thickness with respect to that of the ore body. After soil removal, the exploitation is developed inside the ore body with a single face or bench wall succession. Usually, gypsum is removed from the top to the bottom of the deposit, leaving single benches 10–12 m high and with a 70° dip, in order to guarantee the stability of the face. Bench configuration can be accomplished by means of horizontal or vertical slices. The horizontal descending slices method allows realization of the consequential environmental rehabilitation simultaneously with mining works and ensures safer working conditions because risks of rock downfalls and collapses at the face are lower.

The equipment and mining methods depend on the features of the ore body and mineral resource. Mining equipment is mainly represented by pneumatic drilling

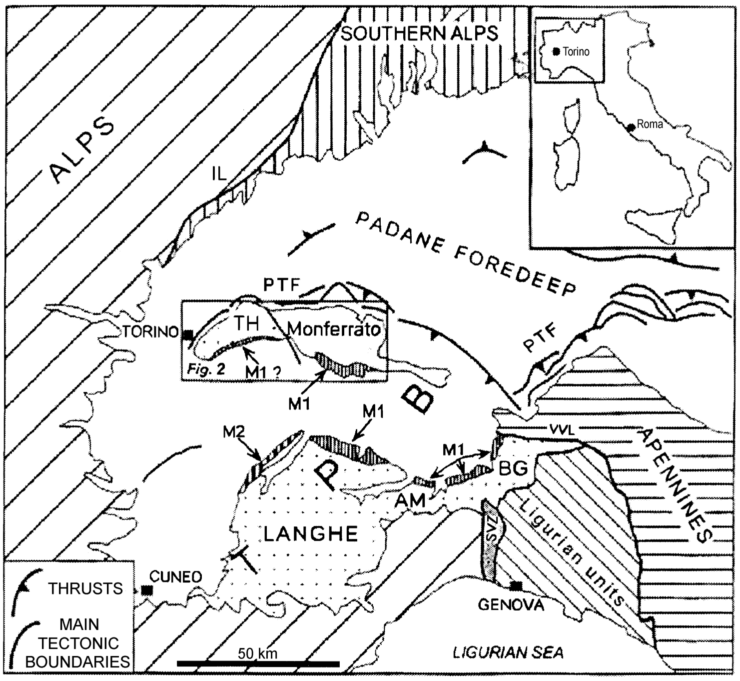

Fig. 1. Structural sketch map of northwestern Italy. IL, Insubric Line; SVZ, Sestri-Voltaggio Zone; VVL, Villavernia–Varzi Line; PTF, Padan thrust front; TH, Torino Hill domain; AM, Alto Monferrato Domain; BG, Borbera Grue domain; M1, Messinian mélange; M2, "normal" Messinian succession (Dela Pierre et al. 2002).

hammers, truck excavators and blast, with hydraulic breakers without blasting, and, in particular cases, just rippers or surface miners. Depending on distances, muck removal is conducted by means of dozers, mechanical wheel shovels, and dumpers for the transport.

Open pit quarries have some advantages, such as the integral exploitation of the ore body, high mechanization and the large size of mining equipment with the reduction of powder in blasting operations. Otherwise, mining works are affected by meteorological conditions because rainfalls stop quarrying activity; gypsum is often marked by lower quality material and environmental impact should be strong and evident.

On the other hand, underground mining meets the requirements of land conservation, has low environmental impact, and the quality of natural raw material is good. The method is traditionally developed with drill and blast techniques, by creating rooms and abandoning pillars, arranged as a chess board; recently a new technology, continuous mining machinery, has been introduced (road header). Several superimposed levels are also created. Each of them is organized with parallel development drifts, following the dip of the gypsum beds, from which the exploitation drifts reach out with a steady angle, following the strike of gypsum strata (Fornaro et al. 1996). Different mining levels are reachable through a helical ramp, which can be used by big lorries.

In order to ensure void stability and safety conditions, pillars and slabs have to be whole and able to stand on their own: rooms are usually stable, with maximum dimensions of 5–7 m in width and 6–8 m in height, whereas squared pillars are normally 6 m side. In order to guarantee safety and healthy working conditions, emergency exits and a proper airway have to be planned on the basis of the number and type of the mining equipment.

Sometimes open pit quarries originate from digging up previous underground quarry structures, by means of uncovering works.

GYPSUM DEPOSITS IN THE MONFERRATO AREA (PIEDMONT, NW ITALY): GEOLOGICAL AND HYDROGEOLOGICAL FEATURES RELATED TO QUARRYING

In Piedmont (NW Italy), large open pits and underground gypsum quarries are concentrated in the Monferrato area where the main gypsum bodies are located. In particular, gypsum belongs to the Gessoso Solfifera Formation (also named Complesso Caotico di Valle Versa in the new geological cartography; see Dela Pierre et al. 2003), which crops out in a discontinuous manner from Moncucco to Ottiglio (about 35 km). Main deposits are located in the municipalities of Moncucco, Castelnuovo Don Bosco, Murisengo, Cocconato, Montiglio, Villadeati, Alfiano Natta, Moncalvo, Calliano, Grana, Montemagno, Vignale, and Altavilla.

The Gessoso Solfifera Formation consists of thick beds of coarse- and fine-grained gypsum (up to 15 m each) with marly interbeds, a few decimetres up to 2–3 m thick (Fig. 2). Locally, thin evaporitic limestone beds are present at the bottom of the succession, whereas marls and clays with gypsum levels (from some decimetres to some metres thick) occur on the top.

The evaporitic succession is organized in up to 150 m thick irregular bodies extending for a few kilometres and being locally intersected by karst phenomena. In places, a few system faults occur in gypsum deposits, which sometimes have a marly filling.

The geological, structural, hydrogeological, and geotechnical features of the gypsum-bearing formation influence the quarrying and determine the interaction between natural phenomena, human activities, and land use. According to both the geotechnical and geomechanical behaviour of the material and the geohydrological features of the deposits, a correct design in the planning as well as management stages of the quarry has to be provided. With regard to gypsum bodies, main geological aspects are represented by marly interlayers, marly fillings of discontinuities, the presence of karst circuits, and the thickness and geotechnical features of covers and bordering formations.

As a consequence, the stability of the quarry structures and the geometrical parameters of the sill, crown, and rib pillars are strictly connected with the drifting depth, thickness and kind of cappings, and geostructural setting of the ore body. Refillings and layers of marl can compromise the stability conditions both in open pit and underground quarries. In open pit quarries, bench height must be reduced; in underground quarries, drifts have to be completely mined in gypsum, leaving gypsum sill pillars thick enough to avoid collapses and raises (Fig. 3).

In case of the cut-off of marl layers, reinforcement of the mining walls has to be provided by means of

Fig. 2. Gypsum strata with marly interbeds, belonging to the Messianian Gessoso Solfifera Formation.

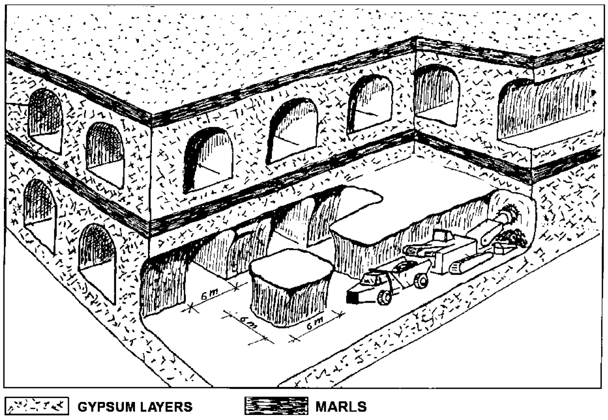

Fig. 3. Exploitation scheme for underground gypsum quarries: drifts are organized on regular superimposed sublevels. They have to be completely mined in gypsum, leaving a coaxial gypsum square or rib pillars.

supporting structures (steel ribs and nets, spritz beton), which require continuous monitoring. Moreover, the marly and clayey deposits (layers or cave and fault refillings) represent a waste in the quarrying production.

Due to high solubility of gypsum in fluent water, it is possible to recognize evidences of Quaternary karst activity (caves, potholes, pipes) in most of the open pits (Moncalvo, Montiglio, Cocconato, Murisengo, Moncucco) and underground quarries (Moncalvo, Moncucco). The permeability of gypsum depends, principally, on the presence and features of discontinuities (opening and frequency), whereas primary permeability is very low. As a matter of fact, stratigraphical and structural discontinuities represent possible ways for groundwater flow, causing an increase in dissolution processes and development of karst morphology.

Consequently, gypsum karst has considerable influence on mining operations, as well as mining operations can produce strong impact on gypsum karst, particularly when water pumping is involved and quarrying interferes with the local hydrogeological setting (increase in flow velocities and dissolution rate, lowering of the water table, breaching of artesian confinement, draining of surface flows, extension of drawdown cones). Risks are particularly connected to the presence of large empty karst caves or caves filled with marly-clayey deposits or water; in those cases, water exerts dangerous pressure on mining.

In Monferrato, a specific case of interaction between quarrying activity and geological, hydrogeological, and territorial setting was revealed in the water inrush into the Moncalvo underground quarry. The event was associated with the development of a surface sinkhole.

INTERACTION BETWEEN EXPLOITATION ACTIVITY AND NATURAL PHENOMENA: THE WATER INRUSH INTO THE MONCALVO GYPSUM QUARRY

The Moncalvo gypsum quarry has been working since 1993 and actually consists of 12 km of drifts, which are organized on three regular superimposed sublevels, connected by a helical ramp, between 170 and 113 m a.s.l. An older open pit quarry is also present near the underground quarry (Fig. 4).

A survey campaign with three drillings (besides the already existing 24 drillings) and piezometers was organized in order to plan the mining operation and investigate the geological and hydrogeological features of the gypsum body. The body consists of regular coarse- and fine-grained 10–15 m thick gypsum strata, which are separated by marly layers, a few decimetres up to 2 m thick. The burden of the exploited gypsum deposit is represented by a succession of marls with thin inter-beds of gypsum and clayey-marly loose material. In the open pit quarry the stratigraphical succession and evidences of Quaternary karst phenomena (caves, potholes, pipes) are better recognizable (Fig. 5).

In particular, four gypsum strata have been recognized, placed in succession from the top to the bottom of the ore body. One stratum consists of fine-grained and three strata are composed of coarse-grained gypsum. Starting from the top of the deposit, sublevels of the quarry are developed in correspondence with the three upper gypsum strata: the first sublevel is set out in the single fine-grained gypsum layer, whereas the other two sublevels take up the coarse-grained gypsum strata. Because of low mechanical resistance and abrasiveness of gypsum and regularity of the ore body, the quarry is exploited by means of continuous mining machinery represented by the road header, instead of the traditional blasting techniques (Fig. 6).

Due to the technical features of the road header, development and exploitation drifts in the production panels do not intersect one other orthogonally as in a blasting exploitation, but take a “lozenge pattern”. For that reason, rooms and square pillars have been replaced by rooms and rib pillars with a smooth and regular profile of the mining walls (Fig. 7), protecting, at the same time, the surrounding gypsum from the typical damages of blasting methods in favour of general stability (Fornaro et al. 1996, 2000). Drifts are straight, have a low dip (<10°) and an adequate radius of curvature in order to guarantee the maximum yield of the road header.

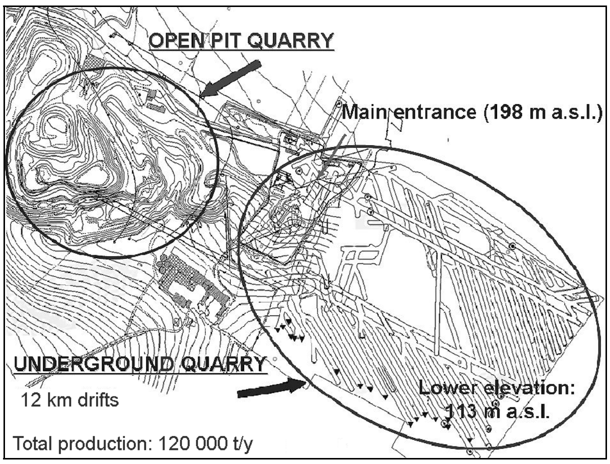

Fig. 4. The quarry area of Moncalvo: the open pit and the underground quarry are marked by circles.

Fig. 5. Karst evidences at the surface in the open pit quarry of Moncalvo.

Fig. 6. The road header used in the Moncalvo gypsum quarry.

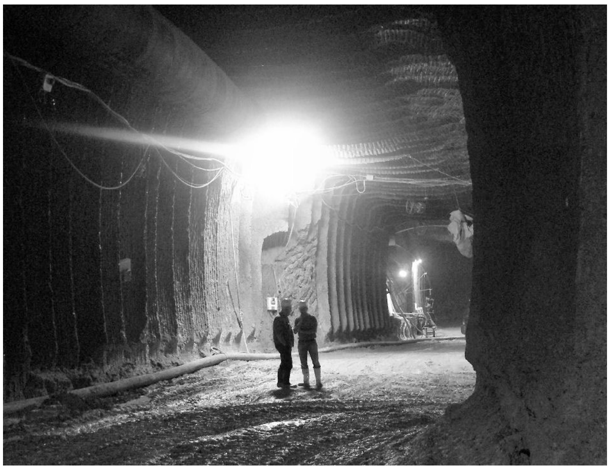

Fig. 7. Profile of the drifts mined with the road header.

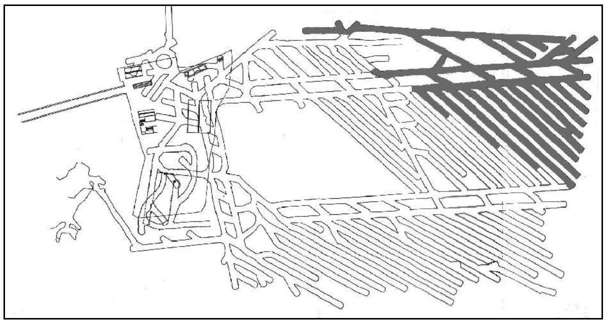

Fig. 8. Area of level 1 flooded by the water inrush. The scheme shows the characteristic lozenge pattern applied due to the use of road header mining machinery.

From the beginning of the exploitation, the whole gypsum body was sound and massive; just occasionally a few discontinuities and dry relict weakly developed karst features (in particular in the SW zone of the quarry, between 150 and 190 m a.s.l.) were detected. In correspondence with some discontinuities, local water inflows, with a limited and constant discharge (<1 l/s) occurred at 129–176 m a.s.l., mainly in the SE area of the quarry. The two existing piezometers recorded other water inflows, with higher discharge and 1–3 bar pressure. Repeated measurements showed a quite stable water table at about 170 m a.s.l.

In the morning of 15 February 2005, during excavation works at level 1, leading to level 2 (134 m a.s.l.), the road header hit a fracture at the mining face with a water inflow of low discharge, but high hydraulic pressure. As a precaution, the workers were immediately moved to the higher drifts. At 6 p.m. an inrush event suddenly took place with water discharge of some cubic metres. During the night, a large amount of water (about 60 000 m^3) and terrigenous marly sediments rushed into the quarrying drift, submerging the road header and flooding lower drifts of level 1 up to an elevation of 139 m a.s.l. (Fig. 8). As a consequence of the inrush event, between 10 p.m. and midnight of the same day, a collapse funnel with a minimum depth of 10 m and maximum diameter of about 20 m was formed at the surface (sinkhole) at the NE border of the quarry area (Bonetto & Fornaro 2005; Fig. 9).

In the next few days, the water flow showed a discharge of about 20 l/s in connection with the hydraulic pressure of about 4 bar in the karst circuits before the event. A pump was installed at level 1 in order to reduce and stabilize the water level in the quarry, which went down progressively to 135.5 m a.s.l.

Fig. 9. Sinkhole at the surface, originating from the Moncalvo underground gypsum quarry.

The inrush event occurred because of the cut-off of a karst cave during mining works, which made the wall of rock between the drift and the natural cave too thin to resist the water pressure behind it. In particular, it has been noted that the point of inrush was located at the bottom of the drift, near to the marly layer separating two different gypsum layers. After drainage, the drift of the inrush was surveyed: a large amount of terrigenous sediments lay in front of the mining face covering the road header. All these sediments were removed and the road header was dismantled and taken away. A hole with the diameter of about 1 m was discovered, connecting the quarrying drift with a natural karst cave (Fig. 10).

During 2005 and 2006, water discharge from karst circuit decreased and became stable at about 8–10 l/s. Water inflows from fractures near the point of inrush (already present before the event) were reduced to a dripping. The pumping was continued and the water level settled at 134.7 m a.s.l.

Fig. 10. Hole in the mining face at the point of the inrush.

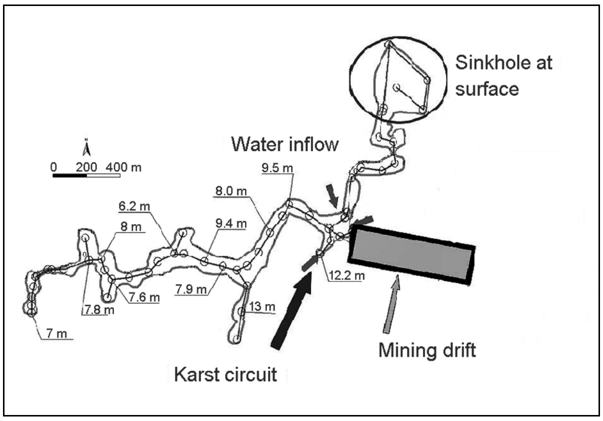

Fig. 11. Scheme of the studied karst circuits after the lowering of water of the inrush event.

Fig. 12. Example of pipes and rooms discovered during the speleological surveying.

SURVEYING METHODOLOGIES AND THE FIRST RESULTS

On account of the water lowering in the drift, the karst cave behind the mining face was scoured. A large room (a few hundred cubic metres) and three main interconnected conduits were discovered, oriented respectively towards SO, NW, and NNW (Fig. 11).

The southwestward conduit is about 10 m long and leads to a siphon from which main water inflow originates. The second pipe extends for about 200 m to the northwest along the marly layer between the second and third strata of coarse-grained gypsum and has a circular diameter of about 5–7 m (Fig. 12). It is located just below the quarry drifts: the distance between the roof of the cave and the floor of the drift varies from 6 to 13 m. The dome roof of the cave suggests that it was a conduit with a full load and gives assurance about the stability of the voids.

The third conduit is about 100 m long and passes through the three coarse-grained gypsum layers with an irregular section. Actually it is completely dry and ends at the sinkhole where a funnel-shaped deposit of terrigenous sediments and woody material coming from the surface is present. During scouring activities, in the large room just behind the mining face, two main water inflows were recognized: the main one came from the siphon of the southwestward conduit, whereas the other one was connected to a discontinuity and showed a discharge of a few litres per second.

Besides safety restoring operations, surface and subsurface investigations were carried out to understand better groundwater circulation, triggering mechanisms of the sinkhole event, origin and quality of water inflows. Subsurface exploration was conducted by means of three borings (SN1, SN2, S24) and the geophysical method, using electrical and seismic refraction tomography, which allowed the reconstruction of local geology and overburden thickness. Borings were equipped with piezometers, and an automatic rain gauge (with hourly measurements) was installed to monitor the groundwater table in relation to rainfalls and mine water pumping.

Water inflows in the quarry (VC, VP3, VBA, and VBB) and in the karst conduits (VS, VB, and VR) were collected and analysed seasonally by means of chemical-physical laboratory tests. Moreover, a weir, equipped with a digital data-logger, was installed close to the point of the inrush in order to measure the level, the temperature, and the electrical conductivity of the water coming from the karst system (Fig. 13).

For over one year, the discharge values measured at the weir were nearly the same (about 10 l/s), with a small increase of about 1–2 l/s during major rainfalls (February 2006, May 2006, September 2006, May 2007; Fig. 14). Similarly, even if data collected have shown

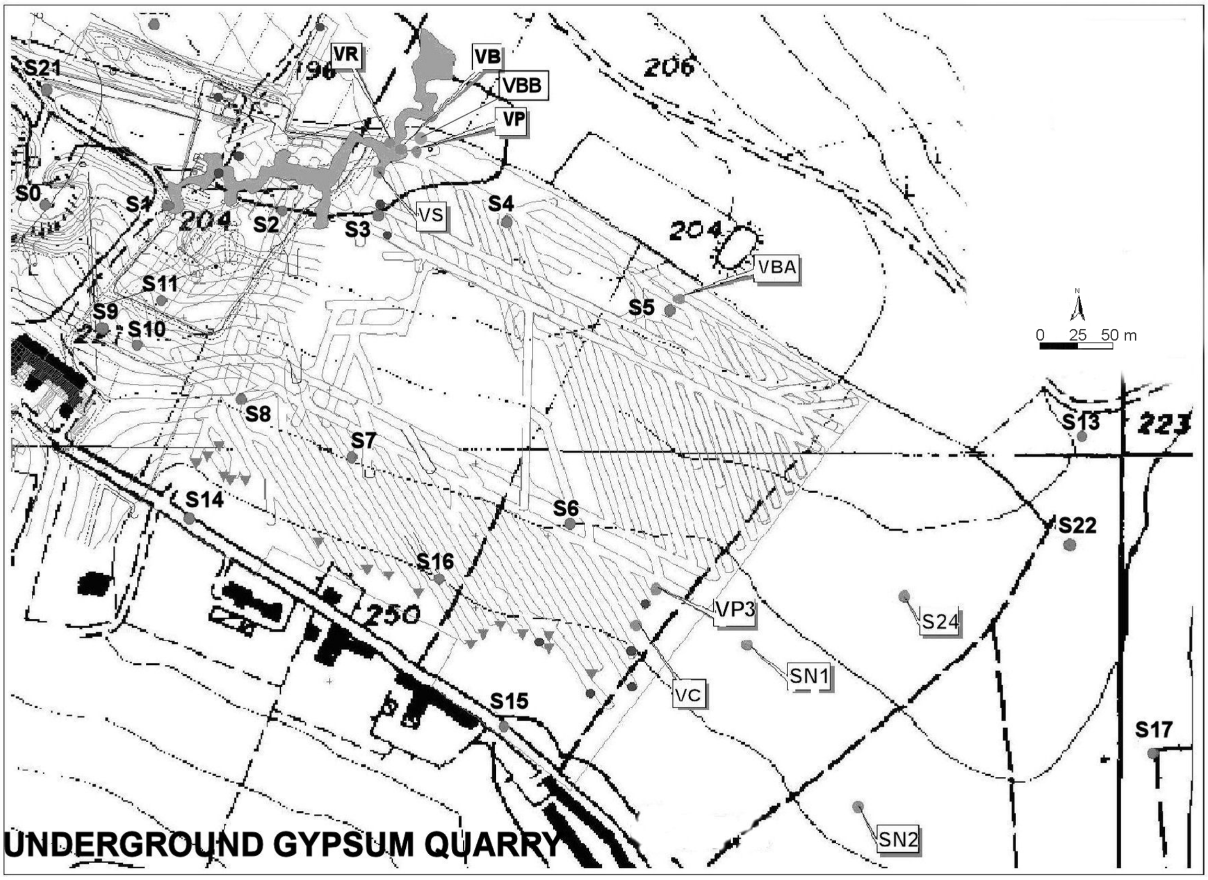

Fig. 13. Distribution scheme of the monitoring points (VC, VB, VR, VS, VP, VP3, VBA, VBB: water inflows; SO–S11, S13–S17, S21–S23: old drillings; SN1, SN2, S24: new drillings with piezometers).

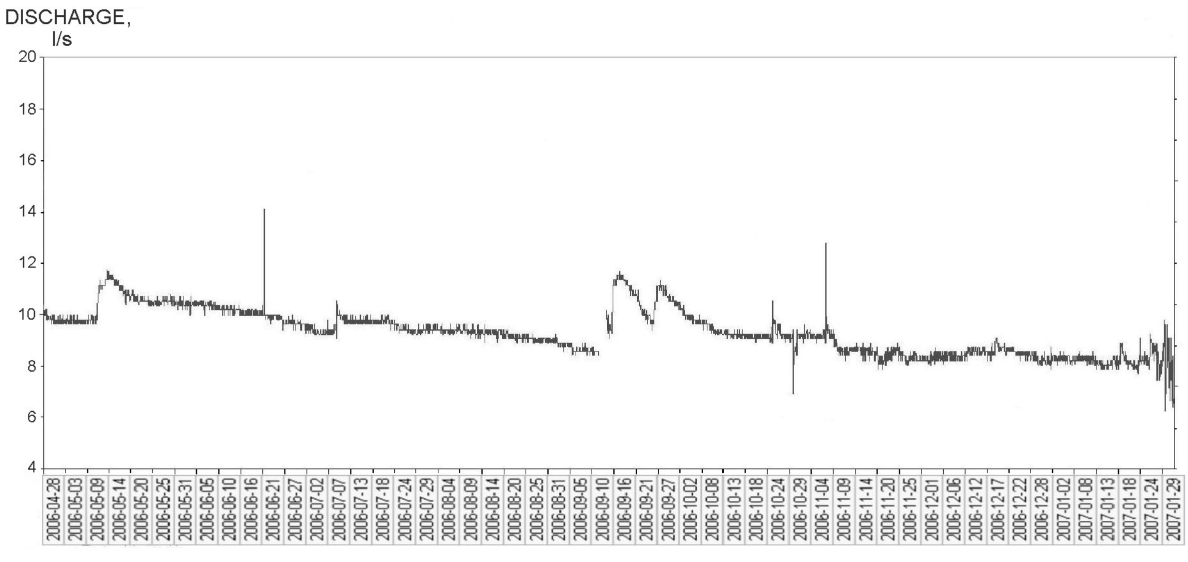

Fig. 14. Trend of the inrush discharge monitored at the weir.

a strong connection between water pumping in the quarry and piezometric measurements, no relation has been observed between the levels of the groundwater table in piezometers and rainfall; all values seem to be independent of each other and different from the value directly monitored in the drifts (SN1 = 214 m a.s.l.; SN2 = 184.3 m a.s.l.; S4 = 225 m a.s.l. at the end of the summer 2006; Fig. 14). Also temperature values recorded in the weir are almost constant with a gentle fluctuation of 0.5 °C, without regard to discharge variations.

LOCAL HYDROGEOLOGICAL SETTING OF THE MONCALVO QUARRY AREA

Chemical and physical analyses of the water inflows sampled in the quarry drifts (VC, VP3, and VBA) show sulphate-calcic water type. In particular, a different quality has been noted for the water coming from the siphon (VS) and for that in fractures (VB, VR). The VS-sample shows a lower mineralization (low concentrations of Mg^+, Na^+, K^+, Cl^-, and SO_4^{2-}) and a higher value of nitrates, which are not present in VB and VR. In order to identify better different inflows in the karst system, the redox-potential (Eh) has been measured: generally, it is positive for the water coming from the surface and negative for slow water that has no connection with it. The inflows VB, VBA, and VBB, as well as the water coming from external piezometers, show a negative Eh, whereas VP3 and VC samples have positive values (Amalberto et al. 2006).

Consequently, the gypsum rock mass is probably characterized by both a slow flow of the water coming from the surface along main discontinuities with a high nitrate-bearing ratio and positive redox-potential (samples in piezometers, VP3 and VC) and a slow flow of the water trapped in the fracture net of the gypsum body and in the surrounding marls with a low nitrate-bearing ratio and negative redox potential, locally intersected by quarry drifts (VBA, VBB) and karst circuit (VB). Full load karst pipes, nowadays still partially active, seem to be the main collector that drains various water inflows.

The independent behaviour of the groundwater table in closely spaced piezometers suggests that discontinuities are not interconnected and confirm the heterogeneity of the water flow in the gypsum rock mass. The low connection of the groundwater table with rainfalls, the consequent stable discharge of the water inflows, and the slow rate of water circulation in the rock mass are probably due to the low permeability and limited outcroppings of gypsum, besides the presence of poorly permeable thick marl and clay covers. Therefore, water moves principally along fractures and stratigraphical discontinuities, such as the contacts between gypsum strata and marl layers. As a matter of fact, one of the main scoured pipes develops at the bottom of the second coarse-grained gypsum stratum, just along the contact with the underlying marly layer. Similar evidences were revealed by drillings: the presence of small karst caves at the contact between the Messinian evaporitic formation (Gessoso Solfifera Formation) and the older Tortonian marls (Sant'Agata Fossile Formation).

EXPLOITATION PLANNING AND MANAGEMENT IN CASE OF ACTIVE GYPSUM KARST

The monitoring programme and investigations are still in progress to define better the hydrogeological structure of the gypsum rock mass and identify the feeding source of the gypsum karst. Useful data can be furnished by means of direct and indirect methodologies, as for example drillings, geophysical surveys, speleological surveys, tracer tests, census and monitoring of springs (natural or formed during mining works). In particular, boreholes have to be provided with piezometers in order to monitor the water table depth in different sectors of the quarry area.

Drillings and electrical and seismic refraction tomography should help to identify the geological features of the deposit, the overburden thickness, and the presence of natural caves. They can be carried out both on the surface and quarry sublevels in order to guarantee a better resolution and establish more precisely the location of geological structures and voids.

The quantity and pressure of groundwater have to be strictly defined, as well as the presence of empty or refilled natural caves, which should represent a risk in terms of quarry stability and general safety. Therefore, during exploitation works, it is necessary to renew geological and structural surveys in order to update project data. In particular, drillings of different directions have to be performed periodically to prevent unexpected and dangerous inrush events; in case of water inflow into the hole, a manometer and a safety valve have to be installed to check the variation of hydrostatic pressure and avoid uncontrolled discharge of water.

Pumping can contribute to a progressive lowering of the water table and allow the exploitation activity to be carried on and deepened by means of new sublevels below the present ones. Pumping discharge has to be usually similar to the water inflows coming from the karst system to avoid inconvenient lack of balance in the natural system and has to be checked by pumping tests. In order to monitor natural and induced strains in the gypsum body, particularly in case of water table fluctuations, it is convenient to make periodically pinch measurements with bend or optical distometers and install pressure cells and transducers (electric or vibrating wire) at the mining wall. By processing the collected data, the stress distribution in the ore body should be rebuilt and represented in a proper 3D-model in order to verify general stability conditions on the basis of the mechanical behaviour of gypsum and overburden. On this subject, in situ tests can be carried out during drillings and samples can be collected for laboratory tests to define useful geotechnical parameters (cohesion, friction angle, specific weight, deformation modulus, elastic modulus, compressive strength, shear strength).

DISCUSSION

A detailed study of the local geological and hydrogeological features is strictly necessary for a proper management and future planning of exploitation activities. Surveying and speleological activity in the case of the Moncalvo quarry contributed to the discovery of the presence of karst conduits with full load, probably fed by lateral and/or basal inflows, which represents the first such case in Italy. In Europe, just a few similar karst systems are present, for example in the Permian gypsum of Ukraine.

In the Moncalvo quarry, considering the volume of the examined caves (about 10 000 m^3) and the amount of the water flow in the inrush event (60 000 m^3), other karst conduits are probably present above the actual groundwater table. At present, water in the quarry drifts is collected in proper basins and pumped outside the quarry in order to stabilize the groundwater table so that the exploitation should continue in the higher quarry panels. Quality evaluations of the mixing of different kinds of water inflows are necessary in order to establish proper use of the water on the basis of sulphate concentration and presence of pollutants. In that case, due to the high values of TDS, electrical conductivity, and sulphates, water is not suitable for irrigation purposes and is reintroduced into the surface drainage pattern.

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Vajumisohust, mille on esile kutsunud karstialadel kaevandamine: Moncalvo kurisu sündmuse (Loode-Itaalias Piemontes) uus käsitlus

Sabrina Bonetto, Adriano Fiorucci, Mauro Fornaro ja Bartolomeo Vigna

Kips on oluline toormaterjal nii ehituses kui muudes tööstusharudes. Piemonte (Loode-Itaalias) peamised kipsilasundid paiknevad Monferrato piirkonnas, kus on ka suured karjäärid ja kaevandused. Seal paljandub kipsi sisaldav kihind, mis on tüüpilise geoloogilise, geostruktuurse ja hüdrogeoloogilise ehitusega, mõjustades nii kaevandamist kui ka suhteid seotud loodusnähtuste, inimtegevuse ning maakasutusega. Eriti tugevasti mõjustab kaevandamist kipsilasundi karstumus, nii nagu kaevetööd avaldavad olulist mõju ka kipsi karstumisele. On käsitletud spetsiifilist juhtumit, mis toimus Monferratos, kui kaevandamise, geoloogiliste ja hüdrogeoloogiliste tingimuste ning territoriaalse paiknemise koosmõju tulemusel tekkis pinnale ulatuv kurisu ja selle kaudu äkiline vee sissetung Moncalvo kaevandusse.