Stability and Environmental Problems due to Groundwater Level Raising in the Abandoned Gavorrano Mine

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Abstract.
The mine of Gavorrano, located in the South Tuscany,not far from the sea coast, has been mined for decades within a metallic sulphures orebody, on a difference in elevation of 500m, in a granitic embedding formation. The pirite orebody was interested in the lower part, by thermal groundwater, originally oursourcing from thermal springs at an elevation about few meters a.s.l.
Ground water had been pumped down to less than 250 m below the sea level to allow the ore mining. After the closure of the mine, about 30 years ago, the water level has been taken into control, but now there is the need to let the water progressively raise. The mining method also adopted a cemented backfill of the voids.
The paper describes this case ando refers in particular of possible instability problems, on the environmental consequences, on the evaluation of groundwater flow and characteristics, telated to the groundwater level rebound after closure, also on the basis of some monitoring techniques.

Key words: abandoned mine, thermal springs, cemented backfill

Introduction

The paper describes some technical problems related with the decommissioning of the Gavorrano mine after his closure in 1981. Gavorrano mine, located in the "Colline Metallifere" mining district in South Tuscany (Central Italy), was one of the largest pyrite mine in Europe during the 20th century. A multi-purpose study started in 1995 to evaluate the possibilities for the realisation of a natural reserve and mining park by recovering the mining area with all its historical mining structures. A major aspect of the rehabilitation involves the evaluation of the stability of underground openings as well as that of the pollution derived from acid mine drainage as a consequence of the mining activity and the recovery of water resources.

Mining methods in the Gavorrano mine

The main orebody exploited in the Gavorrano mine was represented by a lenticular mass of pyrite, vertically developed for about 400 m. This orebody was embedded between a foot wall in a formation of porphyritic granite and an hanging wall in a massive metamorfic limestone taht separates the pyrite from a very permeable limestone ("Cavernoso" formation). At the base of the orebody there was a micaceous quartzite formation.
The geological conditions of the orebody required to adopt a backfilling exploitation method, since caving methods would cause too high settlements at the roof wall in limestone and consequently important water inflow towards the exploitation voids; at the same time, the adoption of an open stope mining method was not possible due to the poor geomechanical characteristics of the pyritic mass.
Till the half of the '60ies, the exploitation method was carried out by means of descending horizontal slices and void backfilling using loose and crushed rock materials. The application of this method for many decades determined with increased evidence several disadvantages: the progressive settlement of the filling materials caused the fracturing of the roof in the limestone formation and therefore the increasing of underground water flow; the settlement of the filling was accompanied by a reduction of the size of the exploited drifts; the huge adoption of wooden supports that remained buried in the fill mass, with consequences on tems of degradation; the difficult working conditions due to high temperatures, humidity and water in the drifts; the high maintenance costs in operation due to the reduced size of the stopes under exploitation.
The progressive introduction of the cemented fill with the same descending mining scheme finally allowed a new condition of the exploitation stopes, completely different from the previous; the following were the main achievements: larger sizes of the drifts, 3.5 m high and 7-8 m wide;

elimination of other support systems for the voids; remarkable improvement of working conditions and stability of the drifts; adoption of high capacity equipment and reduction of the number of simultaneous working stopes; definitive control of settlements in the overburden.
The cemented fill was made with limestone aggregates, obtained from a quarry close to the mine area, with a cement content of about 160 kg/m^3 and with an optimum water/cement reatio of 0.8-1.0. The back filling of the exploited drifts was carried out by continuous pneumatic piping.

Figure 1 *Transversal Section of Gavorrano site. 1) "Cavernoso" limestone; 2) Jurassic limestone; 3) Micaceous quartzite; 4)Granitic formation; 5) Granite with fine texture; 6) Pyritic orebody; 7) Methamorphic boundary.*

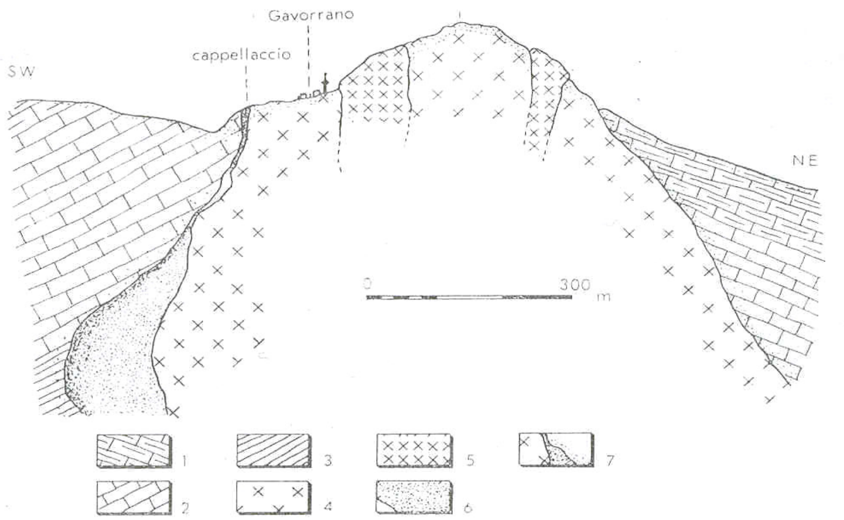


Figure 2 *Surface cracks at Gavorrano hill due to subsidence*

Hydrogeological conditions and modification due to mining operation

The hydrogeological system in the Gavorrano area is represented by the presence of three sub-systems: a superficial alluvial system, a Karstic system and a deep hydrothermal system. Waters from the last two systems have been forcefully mixed by human action through mining. The pre-existing groundwater circulation, with springs placed at the maximum height of 180m a.s.l., was depressed down to -250m a.s.l., when the old thermal springs (Bagno di Gavorrano) were drained through the underground drifts system. Hot springs (up to 47°C) were found during mining in specific ore bodies.

A groundwater balance was calculated by attributing different permeability classes and coefficients of potential infiltration to the several liyhotyped and computing the contributing areas for each lithotype.

Average annual rainfall in the area ranges between 750 and 800 mm y^{-1} with an average evapo-transpiration of 430 mm y^{-1} and a rainy season lasting from October to February with the maximum average monthly rainfall in November (120 mm) and very low precipitation in summer (20 mm in July). According to these data, the calculated evapo-transpiration and a series of infiltration coefficients, 1.1 Mm^3 of water form the annual groundwater recharge. It is important to note that rock mass properties, especially hydraulic conductivity, were strongly and permanently influenced by mining and subsequent induced processes (e.g.: tunnel presence, the increase of fracturing degree and the enlargement of existing fractures by acid water circulation and water level lowering which locally increased karst solution). In fact, tunnels and drifts form a drainage network characterised both by voids and refilled spaces.

The flooding of mine levels is without doubt an important cause of instability for water properties. The reason lies in the fact that rock re-saturation and the filling of mining drifts are associated with the washing out of the sulphate-rich and heavy-metal-rich pyrite oxidation products. Up to now the analyses of the pumped waters have pointed out constant chemical properties. It will be necessary to verify the parameters when the old sectors of the mine are flooded. The new data and the discharge from the new pumping system highlighted the remarkable quantity of the water resources, in particular the volume of the thermal waters (with temperature of 38-40°). All the toxic elements (As, Hg, Pb, Cr, Zn, etc) were found in traces and the water was almost free of contamination of nutrient parameters (nitrate, phosphate, etc...). Sulphates are well beyond the allowable threshold value, while iron and manganese components change from sample to sample. The acidity was quite stable (6,5).

The hydrogeological model, after the acquisition of all data, make a large schema of the water situation of the Gavorrano mine area. The campaigns, served to formulate a diagram of the hypothetic flow directions to control the ancient spring (Bagno di Gavorrano), its re-activation and water table in the mining area . Data acquired during the second phase of the mine flooding (from -140m a.s.l. to -110m a.s.l.) the fives control points (boreholes) did differ considerably with respect to the previous results. Just one borehole showed important differences in the water table level. This one is located on the main fault, in the centre of the village of Bagno di Gavorrano near the ancient Bagno spring, and it was supposed that the two aquifers (superficial and Karstic-hydrothermal) were connected by the same fault and the meteoric waters could recharge/discharge according to the amount of rainfall. So the level graph of this borehole shows the step trend due to the adjustment of the water table. On the whole, the level of the water table in this area has not changed from the last value recorded just before the second phase. The level of the water table in the mine was raised from -140m to -130m a.s.l., with the shutdown of the pumping system. There after, at one-month intervals the water level was raised to -110m a.s.l.. The reason for raising the water level only 30 meters can be sought in the geometry of the tunnels in the Gavorrano mine. The majority of the galleries is already flooded and located below -140m a.s.l.. However there is an another important chapter in the history of the mine and in the exploitation methods between -140m and -110m a.s.l.. . The deeper tunnels are the most recent; those closer to the surface are older and pose greater structural, chemical and hydrogeological risks therefore the flooding must go slowly. Now the water table is stable at -110m a.s.l., forced by the pumping system.

Groundwater level recovery is typical of the closure of mines. It is a common process that can give important information for understanding the effects, starting from the data recorded during the water level lowering and some occasional or accidental water risings. The control of groundwater rebound, in progress at the Gavorrano mine since August 1995, is regulated by a submersible pumping systems. These systems consist of three pumping points immerged in different shafts of the mine (Impero, Roma and Rigoloccio). They are adopted to avoid too fast a rising in the groundwater level, which could induce turbulent flow and internal erosion of the back-filling; excessive hydraulic gradients and groundwater re-emergence at the surface within inhabited areas (Bagno di Gavorrano). The first phase of rebound was from the level -250 m.b.s.l. reached the level -140 m.b.s.l. (august- ctober 1995); in the second phase the level rised at -110 m.b.s.l. (may-august 2005), the third phase up to -80 m.b.s.l. (august-december 2006). Furthermore, the controlling of the rebound allows us to evaluate the volume of water storable within the mine voids system, as well as the changes in the chemical composition of drainage waters. The passage of the Second World War front between 1944 and 1945 caused a forced water level rising and, together with data collected since 1995, these are the only ones available for the mine. Data for the 1944-45 forced rising are available for the main mining centers of that time. The data of the water level rising and the pump discharge neeeded to maintain prefixed water level during each flooding step suggest a power law trend for the groundwater level rise with decreasing rate and with the general form:

$$\Delta H = -(Ht+Ho)*\exp(-a * \Delta t) +(Ht+Ho)$$

where Ht and Ho are the initial and final groundwater level elevations, and Δt is the elapsed time. In fact, the rising rates at Boccheggiano-Gavorrano and Valmaggiore are quite similar while at the Rigoloccio the rate was lower (Crosta & Garzonio, 2000). The recent records were compared with the old ones by putting all the rising steps (from -197 m b.s.l. to -143 m b.s.l., because initial water level rising between -236 m b.s.l. and -197 m.b.s.l. was uncontrolled.) in sequence, without considering the steady level intervals. It must be stressed that the mines were separated from each other during the 1944-1945 period, and have only been linked since 1969. Since 1995 the pump discharge has remained almost constant at 65 l/s, with the exception of three periods of heavy rainfall with discharge until 110 l/s. Recently, in particular during he last phase, in some steps, the discharge was being lowered. Considering the fact that the meteoric waters in the last years were approximately the same quantity, we can suppose the aquifer system is wider than before, because the water has found new ways in the fractured rockmass.

This allowed the storage of about $550*10^3$ m^3 of water storage. Using the data recorded, in a complete way, during the two phases (1997, 1998) of increased discharge, it was possible to perform a recession analysis which gives us a good insight into the aquifer structure. Starting from these data and the recession analysis, confirmation of the previous results concerning the groundwater balance was obtained. In fact, according to the recession analysis, the average water resources that are renewed yearly amount to 2.2 M cubic meters or 66 l/s.

These values are quite comparable with the average yearly pump discharge (65 l/s or 2.08 M cubic meters). Finally, by comparing these data with the ones obtained by the effective infiltration analysis (1.1 Mm^3) it emerges that almost 1 Mm3 of hot water flows regularly from the deep circulation system into the mine every year.

Figure 3 *Pump discharge decrease.*

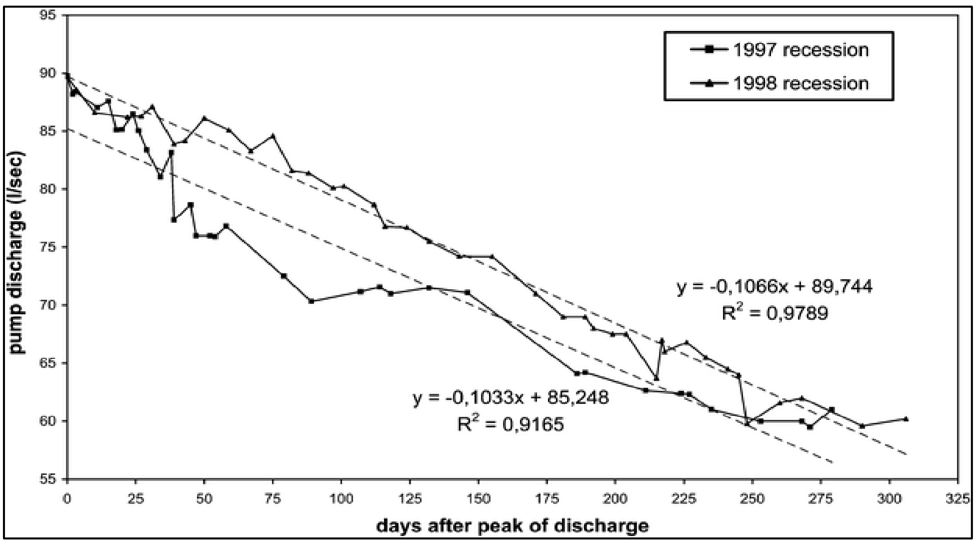
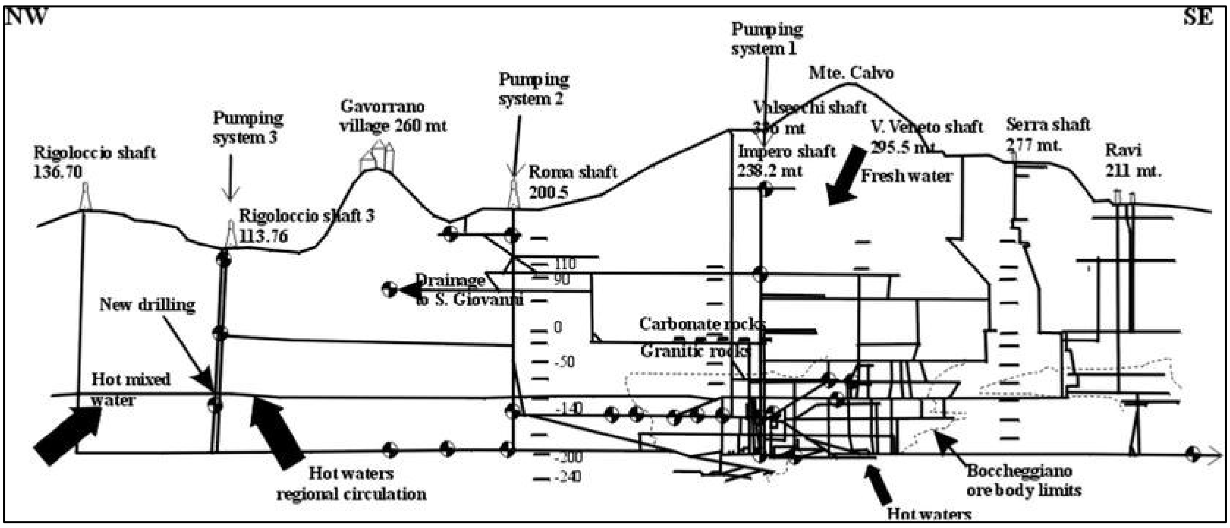


Table 1 *Chemical analysis of some thermal springs in Tuscany (Italy)*

	Poggetti Vecchi (mg/L)	**Bagno di Gavorrano** *(1324)* (mg/L)	**Saturnia** (mg/L)	**Gavorrano mine -140m a.s.l.** (mg/L)	**Gavorrano mine -80m a.s.l.** (mg/L)	**Gavorrano mine** (pumped waters)
$T(°C)$	37	34,1	37	37,5	20,7	36
pH	6,65		6.09	2,77	2,91	6.5
Ca^{2+}	541,08	328,02	600	430	519	405
Mg^{2+}	116,697	59,89	130	174	254	97
Na^{+}	36,784	29,70		40,4	69	46
K^{+}	3,44			7,14	9,09	12
HCO_3^-	244,05	253,00	660	0	0	
SO_4^{2-}	1440,87	844,37	1450	1967	2611	1278
Cl^-	46,089	28,48	50	33,5	23,09	32

At a regional scale it has been observed that sulphate waters commonly spring from the Cavernous limestone and from intrusive rocks. Calcium bicarbonate waters are mainly associated with carbonate formations and small depths and are considered the less mature water class. Gavorrano mine water samples can be clearly differentiated in two main groups: "superficial" bicarbonate waters (from levels +240 m a.s.l., + 155m: Mg-Ca, +90 m: Ca-Mg-HCO_3) and deep sulphate waters (Ca-Mg-SO_4, -80 m b.s.l., - 110 m, -140 m, -200 m). This grouping can be done on the basis of the sulphate (from sulphide oxidation and evaporites solution), iron and silica contents and it is also suggested by the few temperature data even if more qualitative observations have been made. A geothermal gradient of about 75°C km-1 has been determined. A water type sub-group, with peculiar characteristics, is composed by four samples all collected within the intrusion in a relatively localised area, and characterised by very low pH values and high TDS contents. The area was characterised by a conspicuous air flow and abundant water presence, with clear and cold waters. The pH values strongly characterise this minor group. All the other sampled waters generally presented values just a little over neutral (7-8). Mine drainage is characterized by an average temperature of 32°C, a 7 to 8 pH value, and it can be classified as a Ca-Mg-SO_4 or a Ca-Mg-SO_4-HCO_3 water, probably as a result of temporal changes and the mixing action caused by pumping. In comparison, the water of the old spring at Bagno di Gavorrano was characterised by a constantly higher Na and Cl content, with a minor SO_4 content. Recently and during the increasing of the discharge, in particular in Rigoloccio Shaft 3, we can observe higher temperature values and lower pH ones (6,3-6,6).

Figure 4 *Scheme of main drifts and shafts in a vertical section across Gavorrano mine.*



Conclusions

The exploitation of the main orebody of the Gavorrano mine has been carried out by using loosen filling between the elevation of about +200 m a.s.l. down to the depth -90 m b.s.l., while the cemented fill has been used from -90 m b.s.l. down to about -200 m b.s.l.

The following stop in water pumping from the deepest stopes has determined the raising and the temporary equilibrium of ground water table at the depth of about -110 m b.s.l.

On the basis of the knowledge of the geomechanical characteristics of the backfill, it is possible to assume that the cemented material presented an high degree of filling voids and godd continuity; in other words large underground movements are not realistic nor predictable in the lower section of the mine. The conditions where the loosen filling have been used is quite different, because of its particular behaviour, the occurrance of wooden elements and the progressive settlements together with the movement of the rock walls could lead to sudden failures.

The interruption of the water pumping from the old mine stopes will determine the growth of the saturation level up to the main drainage tunnel, located at the elevation of +70 m a.s.l. In this condition it is predictable that some sudden structural failure of undergroung residual voids can occur (in the loosen fill mass or from the fractured roof), with a blow on the water volumes and possible quick exit of mud from the drainage tunnels and also from surface springs which were no longer active due to the mine operations of water pumping. These events are possible, even if their the intensity doesn't seem to be relevant as the mining methods have left only small open underground voids.

The study described includes highlights the great importance of continuously monitoring the water level and water chemistry changes, both during and after the completion of mining operations. The importance of this monitoring is illustrated, for example, by the rising rates observed at different mining sites (Valmaggiore, Gavorrano, Rigoloccio) during the forced Word War II pumping arrest. The pH of the Gavorrano mine waters is almost neutral. This may be due to the content of alkaline minerals within the carbonate rocks mass, both in the upper mine levels and the tectonically lowered rock mass near the main faults of the area (thermal water flowing up at the Rigoloccio mine). The neutralisation of the naturally acid waters, which derive from iron sulphide oxidation, because of their contact with air and water after tunnel excavation, could also be the result of the material used to back-filling excavations (limestone blocks together with clay and cement). The chemical monitoring has pointed out a small trend of lowering of the pH values (6,4). The TDS content is high, but the quantities of polluting elements are low.

The groundwater balance and the discharge rates pumped confirms the volume which could be stored, and the important presence of a thermal deep circulation coming from far away. In the present phase of the water rebound the proposals of different re-utilization project of the waters are realizable as well as the necessity of collecting new monitoring data (necessary to increase the conceptual and numerical model of the water flows), before further change in elevation of the recovering water table.

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