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SUBSIDENCE AND SLOPE DEFORMATION PHENOMENA IN THE GAVORRANO MINING AREA (Tuscany, Italy)

ABSTRACT: CROSTA G. & GARZONIO C.A., *Subsidence and slope deformation phenomena in the Gavorrano mining area (Tuscany, Italy)* (IT ISSN 0391-9838, 1996).

Subsidence phenomena, especially in mining districts with high extraction ratio and more surficial working, can play a major role in activating slope instability processes. In fact, subsidence can improve the action of gravity increasing the state of stress within an overlying hillslope. In the literature very few papers have been published about this problem. In this work it is presented a case history from Gavorrano, an old pyrite mine within the Metalliferous Hills Mining District (Tuscany, Italy). A huge subsidence phenomenon, interesting a hillslope, has been able to trigger an important slope instability process mainly by accentuating some possible natural instabilities. Field work, both at the surface and within the mine tunnels, allowed the geological and the rock mass characterization. The collected data have been successively employied to perform some simplified numerical simulations (by the distinct element method) to help in a better understanding of the phenomenon and in deciding about possible deep seatedness of the induced slope instability and the role of the mining protracted for almost a century.

KEY-WORDS: Subsidence, Slope deformation, Pyrite, Mining, Numerical modelling, Tuscany (Italy).

RIASSUNTO: CROSTA G. & GARZONIO C.A., *Subsidenza e deformazioni di versante nell'area mineraria di Gavorrano (Toscana)* (IT ISSN 0391-9838, 1996).

I fenomeni di subsidenza possono costituire una notevole conseguenza dell'estrazione di grandi quantità di minerale specie in zone ove l'estrazione avviene a media o piccola profondità. La subsidenza può infatti causare la variazione dello stato di sforzo nel versante sovrastante, inducendo aree di prevalente trazione e altre di compressione. Inoltre, la variazione topografica conseguente alla subsidenza può spesso facilitare l'azione della gravità sui pendii coinvolti. Nella letteratura tecnica riguardante i fenomeni di subsidenza si trovano relativamente pochi riferimenti agli effetti sulla stabilità di versanti. Il caso presentato in questo lavoro è quello della miniera di pirite di Gavorrano (Colline Metallifere, Toscana) ove l'estrazione durata circa cento anni ha indotto la rimobilizzazione di un settore di versante a seguito di un fenomeno di subsidenza. La raccolta di dati geologici e geomeccanici, in superficie come in sotterraneo, ha permesso di caratterizzare l'area in esame offrendo lo spunto per l'esecuzione di alcune modellazioni numeriche col metodo degli elementi distinti. Tali modellazioni hanno avuto come scopo sia la comprensione del fenomeno che la stima del coinvolgimento del versante. Quest'ultimo motivo è infatti importante qualora si desideri arrivare ad una classificazione del fenomeno di instabilità e in particolare per valutarne le dimensioni. Ne è risultato, sia per motivi geometrici che per la relativa lentezza di realizzazione, che tale instabilità può essere classificabile come una deformazione gravitativa di versante, in cui una perturbazione di origine antropica e della durata complessiva nota di circa un secolo, ha favorito l'azione della forza di gravità.

TERMINI CHIAVE: Subsidenza, Instabilità di versante, Miniera di Pirite, Modellazione numerica, Toscana.

INTRODUCTION

Gravity is the driving factor in a deep seated slope gravitational deformation. Nevertheless, the action of gravity being always present, it becomes more effective when some external factor increases the degrees of freedom of the involved system. Subsidence phenomena are a clear example of such preparing factors allowing the development of very large deformations. The interaction of slope stability with mining induced subsidence is a more specific example of such a process, common in nature but rarely described in the technical literature both treating slope instabilities and mining consequences. At the same time, pre-existing slope instabilities interacting with subsidence pheno-

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mena or subsidence phenomena triggering new landslides in sloping ground surfaces are both possible scenarios. Then a complex relationship can rise up in sloping grounds overlying mining excavations and geological, geomorphological and geomechanical characteristics must be known for a better understanding of such a relationship and of the possible mechanism and evolution.

This research was prompted by a series of observations performed during the study of the Gavorrano mining area, within the Metalliferous Hills mining district in southern Tuscany, one of the largest pyrite mine in Europe for more than a century up to 1981 and since then in maintenance. This multi-purpose study aims to realize a natural reserve and a mining park by recovering the whole area around Gavorrano with all its mining structures. The environmental rehabilitation of the area involves the recovering of quarries, tailing dams, lagoons and surficial mining areas by reforesting, stabilization, or restoring of significative old mining structures. One more aspect of the environmental rehabilitation involves the difficult evaluation of underground water resources in a complex system where karstic and hydrothermal waters have been forcely mixed by anthropic action realized through mining. Deep mining works (almost 500 m of production levels) have been realized in this area by lowering the existing water table to almost -250 m b.s.l. and changing completely the old groundwater circulation drying some old thermal springs (Bagno di Gavorrano, 30 m a.s.l.). Hot water springs, up to 47°C temperature, have been found in the Rigoloccio area and mixed with the karstic flow system by the complex system of mining tunnels. Hydrothermal and fresh waters could be recovered for civil uses, especially during the dry and touristic season, also implementing the touristic resources of the area. This exploitation could avoide excessive water level rising up to its emergence in presently urbanised areas. Eventually, the creation of a mining park implies the restoring of some of the underground structures (tunnels, shafts, winches, raises) at different levels maintaining a large safety margin.

GEOLOGICAL SETTINGS

The Gavorrano area, placed in the Metalliferous Hills, few kilometers from the sea is characterised by hills rising from a very flat plain up to an elevation of 450 m a.s.l.. The Tuscan geological series outcrops entirely in this area together with a Pliocenic (4.9 My) quartz-monzonitic intrusion oriented NNW-SSE (Bertini & *alii*, 1969). The permian metamorphic complex (phyllites, schists), under the Tuscan series, outcrops N to Gavorrano, while the Tuscan series outcrops all around the area. The Cavernoso Limestone is a brecciated and karstified limestone (Noric), partially metamorphosed at the contact with the intrusion, covered by the Avicula limestone and marl and subsequently by the Liassic Massiccio Limestone. These are the most important geologic formations implicated in the study (fig. 1) while the upper part of the Tuscan series

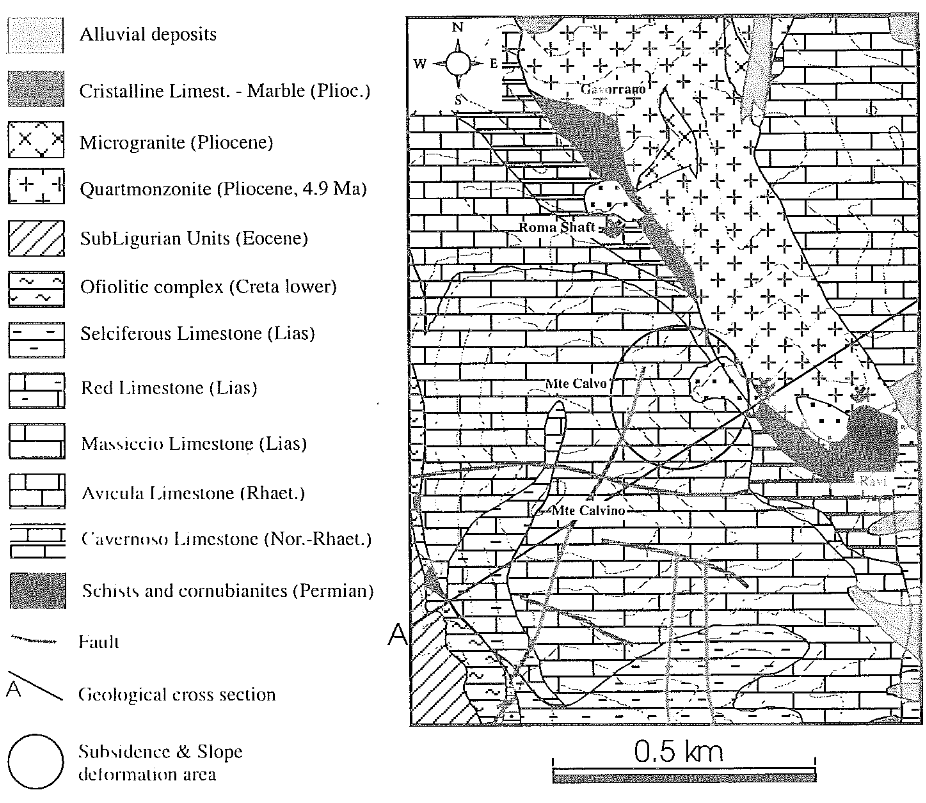


FIG. 1 - Geological map of the Gavorrano mining area.

(Ammonitico Rosso, Calcare Selcifero, Marne - Marl - a Posidonia, Diaspri, Scaglia, Macigno) outcrops more southward. Finally, the eocenic flysch concerns only part of the more surficial mining works in the northern area. The quartz-monzonitic intrusion (BARBERI & *alii*, 1971), characterised by some dikes, oriented prevalently N-S, NE-SW and NW-SE, is quite weathered in the outcrops and it is often bounded by a thick zone of loose soil like material called «renone». On the contrary, no weathering and alteration can be observed along some of the mining drifts, especially far from the main ore bodies, where pyrite is present in minimum concentrations. The pyritic ore was commonly cultivated in lenses or bodies of irregular shape placed at the contact between the intrusion and the Calcare Cavernoso, and sometimes along the main faults (ARISI ROTA & *alii*, 1971).

Karstic conduits are considered quite common in these limestones and many karstic features can be recognized in the field. As a consequence karst played an important role on the properties of the rock mass and also on those of the in place ore bodies. Furthermore, chemical reactions causing the decrease in pH of circulating water and the consequent dissolution of iron sulphides could have been at the origin of more voids within the rock mass. This is particularly important because of the location of pyritic ore bodies right at the contact between quartz-monzonitic intrusion and carbonatic formations as well as for the presence of ore veins and impregnations within carbonatic rocks.

In fact, pyrite is a quite unstable mineral breaking down quickly under the influence of weathering. Hence, it seems important to list both the chemical reactions generating acidity (H^+) through the weathering of iron disulphide minerals and those inducing oxidation of pyrite to produce ferrous and ferric sulphates and sulphuric acid.

The most important acidity generating reactions are:

$$2FeS_2 + 7O_2 + 2H_2O = 2Fe^{2+} + 4SO_4^{2-} + 4H^+ = 2FeSO_4 + 2H_2SO_4 \text{ (pyrite oxidation)} \quad (1)$$

$$Fe^{2+} + 1/4O_2 + H^+ = Fe^{3+} + 1/2H_2O \quad (2)$$

$$Fe^{3+} + 3H_2O = Fe(OH)_3 + 3H^+ \quad (3)$$

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15\ Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad (4)$$

while those for reaction of the products derived from pyrite oxidation (eq. 1) are:

$$4FeSO_4 + 2H_2SO_4 + O_2 = 2Fe_2(SO_4)_3 + 2H_2O \quad (5)$$

$$3Fe_2(SO_4)_3 + 12H_2O = 2HFe_3(SO_4)_2(OH)_6 + 5H_2SO_4 \quad (6)$$

Among the listed reactions, those expressed by eq. 1 and 5 require aerobic conditions while 6 is a hydrolysis reaction that can proceed without air and is mainly bacteriologically controlled. For our purposes, we must remember that the opening of such a large mine is a way to accelerate these reaction by allowing an easier circulation both of air and water. Again, sulphates and sulphuric acid react with clay (e.g. in the «renone» material) and carbonate minerals (present throughout the carbonatic formations) to form secondary products including manganese and aluminium sulphates. Tertiary products can result from the reaction of these minerals generating calcium and magnesium sulphates.

It must also be stressed the importance of these reactions for environmental problems concerning the water percolating through the tailing dams, the floatage basins of S. Giovanni and the one educted from the mine as well as their role in generating hot water springs because of their exothermic nature (eq. 1).

MINING ACTIVITIES

The ore (pyrite) was mainly distributed in a series of lenses of different shape, size and location with respect to the intrusion and the sedimentary rocks. Different ore lenses were identified by different names (of which the most important are: Praga, Unione, Montecatini, Boccheggiano with an average dipping: 50° W; Monte Calvo, Querceta-na, Vignaccio, with an average dipping: 60° E, etc.) and were preferentially aligned N-S. Figure 2 is a sketch, not in

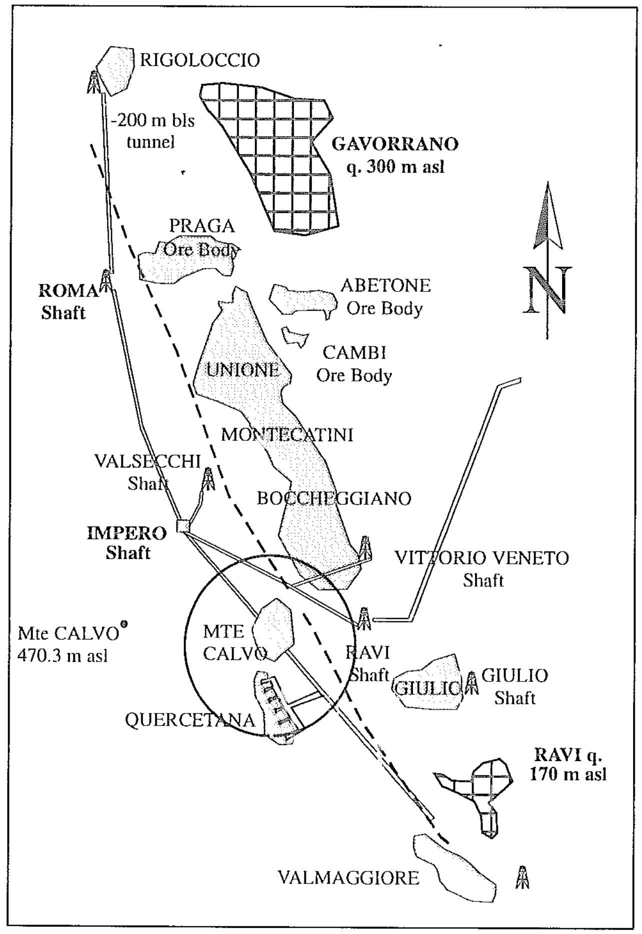


FIG. 2 - Sketch showing the location of main ore bodies (not in scale), adopted names and more important drifts and shafts.

scale, representing the spatial disposition and the name of main ore bodies, where the whole mining resource is developed for a total length of 5 km. Figure 3 is a geological cross section illustrating the relationships between intrusion and enclosing carbonatic formations.

Few detailed information are presently available, even if we know a lot thanks to the official Bureau of Mines Reports since 1898 up to 1981, when ore extraction stopped both for decrease of pyrite price on the international stock market exchange and as a consequence of some major failures within extraction sectors. Activity continued only with maintenance of main access, haulage levels, shafts and pumping equipment.

The extraction advanced by alternated parallel subhorizontal slices, 2 to 3 m wide, starting from a unique transversal both upward and downward (top slicing) accordingly to the different mechanical characteristics of the ore mineral. Generally, the ore excavation proceeded upward, from footwall toward the hanging wall. Backfilling was commonly adopted during the extraction before passing at successive intermediate slices, but backfilling material also changed conspicously in type and quantity during the mine history, from tree branches to mining wastes, sand and blocks placed dry with or without binding material (clay) (hydraulic backfilling), up to mixtures of cement and small rock blocks. Successive changes in the excavation techniques brought into new sizes of ore excavation tunnels up to 5.5 m wide. Mining began at the upper levels (about 200-250 m a.s.l.) close to the topographic surface and continued progressively into deeper levels, up to a final absolute elevation of - 236 m b.s.l.. As a consequence, the piezometric level has been gradually lowered below the minimum elevation to allow mining and the successive rising of the water level has been controlled during these very last years. At the same time, some surficial hot and cold water springs disappeared allowing for the emplacement or spreading of new dwellings (e.g. Bagno di Gavorrano). During the century of industrial exploitation of the ore reserve, more than 10 Mm^3 of tout-venant have been mined out with placement of about 6.5 Mm^3 of backfilling material and leaving almost a void volume of 3.6 Mm^3. During the last 15 years of maintenance, 1.98 Mm^3/year of water have been educed suggesting a total time for void infilling of about 22 months. Nowadays, the water level is under controlled rising and reached a maximum elevation of about - 153 m b.s.l.

Subsidence episodes accompanied mining activities during their entire history. Since 1908, when some buildings close to Gavorrano where damaged by relative settlement along the quartz-monzonite and limestone contact, subsidence and underground failures have been reported. Nevertheless, absolutely no hint is done about the most evident subsidence phenomenon located on the E flank of Mt. Calvo.

MINING INDUCED SUBSIDENCE BELOW HILLSLOPES

Very few references exist in the technical literature about effects of mining activities on hillslope stability. Shallow slides in spoil heap material, deep rotational and translational slides as a consequence of changes in springs location and piezometric level or surcharge, founder by reactivation of fault and disaggregation of strata are the main slope instability phenomena listed by JONES & *alii* (1991). In particular, JONES & *alii* studied some deep seated landslides, in the South Wales Coalfied region, generated by slope instability interaction with mining subsidence during the last 130 years and where other slope failures have been described as a consequence to deglaciation. Some more studies have been performed by PELLS & *alii* (1987) about subsidence and slope instability phenomena along rock cliffs interested by underground coal seam excavations. Failure of large interbedded shale and sandstone blocks have been observed as a result of deformation and development of large tension cracks with relative displacement. Cracks were located up to 60-70 m beyond the slope crest. More interesting for this study are the earlier research presented by FORRESTER & WHITTAKER (1976), concerning the effects of mining subsidence on colliery spoil heaps overlying some mined out coal seams, and those presented by HOEK (1974) and BROWN & FERGUSON (1979) on progressive hangingwall caving. FORRESTER & WHITTAKER (1976) show that the vertical subsidence under spoil heaps is larger, more spreaded and appears a little in advance than for natural flat surfaces, with the point of maximum subsidence generally coincident with the slope crest. BROWN & FERGUSON (1974) discuss the relation-

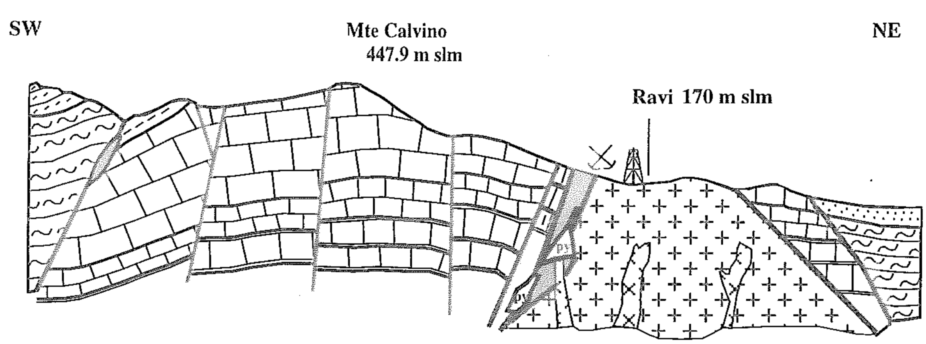


FIG. 3 - Geological cross section directed NE-SW and passing through the Mt. Calvo area.

ship among depth of extraction levels, tension crack size and rock mass properties. Furthermore, an evident sub-circular pattern of cracks have been detected over mining areas with a good correspondence to the progress or the permanent boundaries of mine workings (SAMMARCO, 1995). Such subsidence induced tension cracks appear throughout the entire slope and also at its foot, increasing in this way both water flow and drainage.

Subsidence features recognized in the area

The Mt. Calvo (468.6 m a.s.l.), located southward from Gavorrano, shows clear surface karst landforms. Pavement karsts and shallow dolines, established on solutionally widened joints and fractures, mark the low sloping almost plateau like top of Mt. Calvo. The E flank of Mt. Calvo, toward Ravi, is characterized by structures that with no doubt can be ascribed to a subsidence process. Cracks with different length, orientation, aperture, relative displacement, depth and continuity have been surveyied (fig. 4a). A subdivision has been performed according to their relative location with respect to the main slope crest. In fact, a change in their global trend can be observed when moving upward and downward from the main slope crest (fig. 4b). Cracks beyond the crest, discernible up to 200 m from the slope crest, have a roughly subvertical N-S linear trend with occasional diversions and branching, and display an increasing length, aperture and jagging when getting close to the crest. Aperture increases from few centimeters up to 2 meters and concurrently the relative displacement between opposite crack edges extends up to 1-1.5 meters. Fractures depth ranges between 1 m and 20 m up to 30 m (as from speleological surveyings organized to implement research data and probably continuing up to 60 m) with a general V shaped aperture and only limited Λ shaped profiles. The average spacing among major fractures ranges between 15 m and 20 m with very few dispersed data.

Quite a different situation can be found starting from and below the hill crest where major composite fractures become more curvilinear with a sub-circular trend while minor fractures result in a radial orientation. The sub-circular depression, with a maximum diameter of about 450 m, is delimited by two main composite cracks and some related scarps to the NNE and the SSE boundaries. The NNE crack is almost 550 m long, 350 m of which are 3 to 6 m wide and 20 to 30 m deep. The SSE crack has a width ranging between 0.5 m and 6 m with a maximum depth of about 10 to 12 m and a maximum aperture in the middle part. Some more concave upward cracks appear at the slope feet suggesting a maximum depression point somewhere in the lower half of the hillslope. The rock mass is generally highly fractured, with major fractures spacing in the order of 5 to 15 m, and large part of the depression is covered by loose debris forming some scree slopes and probably masking some more open fractures.

On the whole, a maximum displacement of some tens of meters (30-40 m) could be inferred by the distribution and aperture of major fractures and prevalently in a downward direction.

Eventually, other fractures are located southward from this main depression always maintaining a sub-circular pattern (fig. 4a). This last fracture system does not show apertures of the same entity as those recognized around the larger depression and sometimes seems generating small scarps in soil. This very last system of cracks can be located right in correspondence of the Quercetana ore body (fig. 2).

Influence of structural features and ore bodies location

For a better understanding of the phenomenon it is fundamental the analysis of the relationships existing among rock mass features, mining activity and the depressed area. This area is located (fig. 1, 2) at the southern end of the Boccheggiano ore body (fig. 4a, b; with mining le-

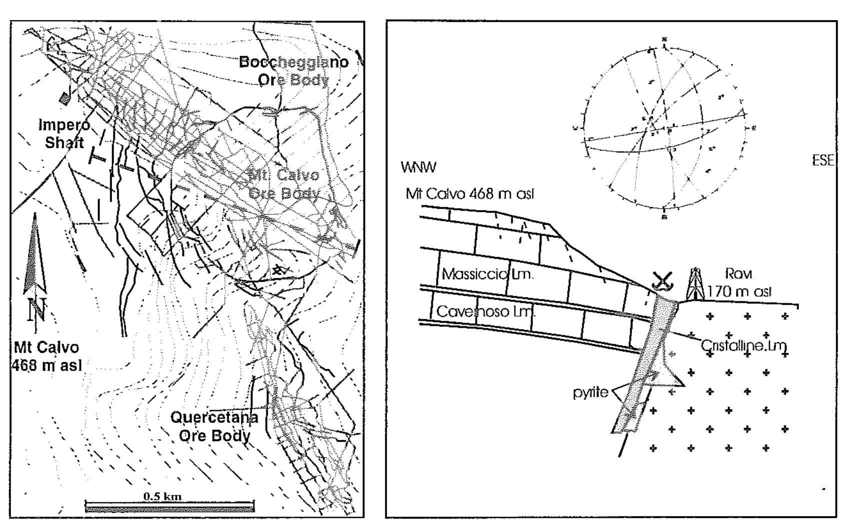
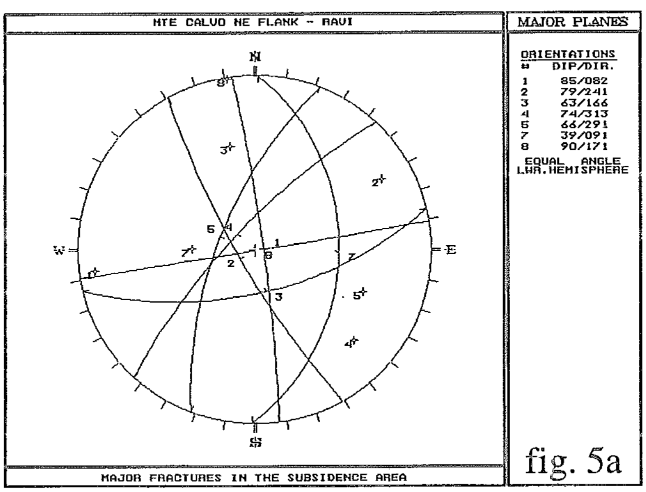


FIG. 4 - a) Pattern of cracks surveyied on the E flank of Mt. Calvo differentiable when below and beyond slope crest because of the different trend, more rectilinear or zig-zagging above the crest and more curved below it; also sketched the Boccheggiano ore body boundary and the location of main drifts and tunnels under the area involved by subsidence; b) geological cross section along the trace in fig. 4a and stereoplot of main discontinuity planes.

vels between +170 a.s.l. and -236 m b.s.l), aligned NNW-SSE, and slightly to the N of the Quercetana ore body, close to the Mt. Calvo pyritic lens (both enclosed between mining levels at +10 a.s.l. and –130 m b.s.l.). Again, the slope (developed between 250 m and 405 m a.s.l.) dips to SE that is in the direction of major drifts and tunnels (developed between +90 m a.s.l. and –205 m b.s.l.), the quartz-monzonite/limestone contact being slightly to the E with a general NNW-SSE trend.

Main discontinuity sets have been identified through geomechanical surveyings (fig. 4b, 5a, 5b) located all over the area both on the surface and along mining drifts. A good rock exposure has been found on the opposite NW side of Mt. Calvo, where a quarry for backfilling material remained opened until few years ago (fig. 5b). Subvertical (80-90°) discontinuity sets with a general N-S direction, roughly parallel to the intrusion border, represent the more frequent and persistent structural feature, both as joint and faults, and frequently characterized by karstic forms. This observation is in very good agreement with the general direction of main open fractures behind the slope crest and at the same time suggests the more common types of instabilities (toppling, falls) along the slope. The same sets are present along the slope where the changing factor is represented by the appearance of more sub-vertical E-W trending discontinuities (fig. 5a). Again, all these discontinuities generally show karstic structures or very persistent and smooth surfaces with rare sub-horizontal to low dipping small steps characterised by fresh rough fracture surfaces.

Small evidences of instability phenomena have been recognized near the slope crest and prevalently by the same mechanisms as cited above (toppling, falls) and in connection with some little vertical cliffs.



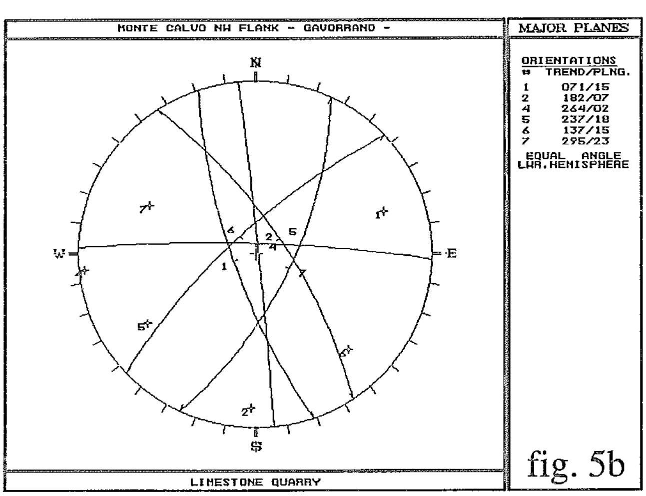


FIG. 5 - Stereoplot of major joint sets recognized from field work all around the mine area, both in coincidence of surface and subsurface outcroppings: a) NE flank of Mt Calvo, subsiding area; b) NW flank of Mt Calvo, quarry area.

SLOPE INSTABILITY MODELLING

The understanding of slope instability evolution and of its changes as a consequence of mining activities is therefore the main problem to be solved. At the same time, the observation of so huge cracks developed in a sub-circular system, the evidences of downslope movement and the depth of mining drifts and ore bodies suggest the existence of a complex instability where vertical and horizontal components are anoumalously distributed with respect to more common slope failures. Nevertheless, a reliable study and in particular a numerical simulation need more geometrical and geomechanical data with respect to the actually available ones. Anyway, a series of numerical simulations (by Udec: Universal Distinct Element Code, Itasca, 1993) has been run by knowing discontinuity distributions (fig. 4b, 5a), location of main ore bodies (Boccheggiano, Mt. Calvo, fig. 2, 4b) and a range of values for rock mass strength properties. In particular, carbonatic formations have been considered as a whole and as the less resistant and more deformable ones, while the granitic intrusion is assumed as strong and rigid. To take into account the successive phases of mining, 6 different excavation steps have been simulated, each one starting only after stress re-equilibration occurred within the back-filling material. This approach has been adopted because ore bodies were completely mined out and being too difficult to simulate the precise mining through successive detailed drifting and backfilling steps.

The most frequent and persistent discontinuity set (fig. 5a) has an apparent dipping angle of 60°, obsequent with respect to the slope (with average inclination of 17°), and with an average spacing value of 15 m to 20 m for major open fractures. Then this discontinuity set has been introduced as an ubiquitous joint system and having noticed in the field the absence of fresh or rough fracture surfaces they have been conferred of relatively low strength parameters. An ubiquitous joint model has been adopted because more representative of field conditions for the carbonatic rock mass while better properties were attributed for the granitic (table 1). Furthermore, because of the presence of discontinuos clay-like material («renone») and of loose pyritic material, lower strength parameters pertain to the contact discontinuities between limestones and the intrusion as well as between pyrite ore bodies and enclosing rocks.

Eventually, relatively weak strength properties have been attributed to the backfilling material reflecting both the unknown or poor quality of the oldest ones as well as to take into account for the incomplete and not instantaneous emplacement.

TABLE 1 - Physical and mechanical properties introduced in the ubiquitous joint model (specific weight = γ, bulk modulus = K, shear modulus = G, friction angle = ϕ, tensile strength = σ_t, cohesion = c).

LITHOTYPE	γ (kN/m^3)	K (GPa)	G (GPa)	ϕ (°)	σ_t (MPa)	c (MPa)
Limestones	25	11	5	35	40	30
Granite	27	44	28	43	40	80
Pyrite	27	2	0.9	33	5	3
Back-filling	15	10	5	30	0.1	0.2

The results of the modelling are illustrated in figure 6 by means of computed vertical, horizontal and total displacement and plastic state. Vertical displacement values (fig. 6 a; up to 12 m) and their distribution stress out the importance of the subsidence process, with a maximum right uphill of the slope feet, in the lower third of the slope, with a maximum depth of almost 180 m. One more secondary maximum is located at the slope crest, close to the more inclined slope sector, and in agreement with the maximum horizontal and total displacement (fig. 6b). A further secondary vertical displacement peak, is placed right at half slope length. Distribution of horizontal and total displacements (max 25 m) identify an irregular zone of movement with varying depth rapidly increasing from the crest (about 80 m) toward the ore bodies (about 200 m) with a minimum depth in the middle of the slope (approximately 50 m). Total displacements computed through a prolonged simulation tend to stabilize around a maximum of 50 m.

Eventually, the plastic state plot (fig. 6c, 6d) makes clear the type of mechanism still in act, that is a well developed state of tensile failure, surficial and well spreaded

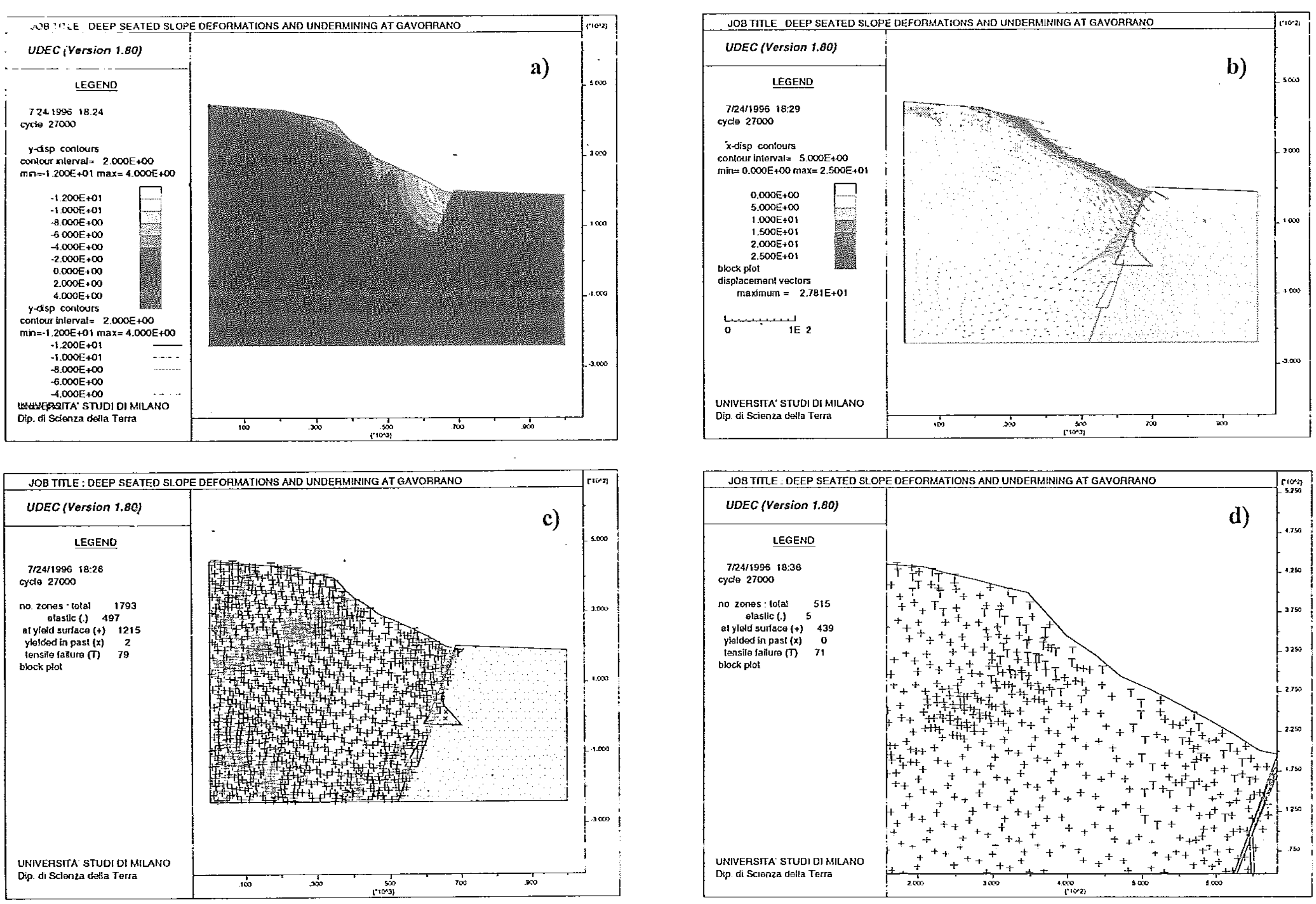


FIG. 6 - Results of a distinct element simulation showing limestone and quartz monzonite in contact together with the simplified shape and position of main pyritic ore bodies (Boccheggiano and Mt. Calvo): a) Countours of vertical displacement component as resulting from numerical simulation; b) Horizontal displacement countours with total displacement vectors; c) Plastic state of rock mass where T symbols stay for tensile failure points; d) Detail of the plastic yielding state from fig. 6c.

behind the slope crest, deep right close to the crest and very deep in the lower third of the slope. Then, this last plot shows a complete rock mass relaxation at the surface as well as at intermediate depth.

DISCUSSION

The collected information allowed the reconstruction of the general instability layout. The main field evidences have been spotted and now can be easily listed: cracks with increasing aperture and relative displacement gradually increasing toward the slope crest and then along the slope itself, very limited rough and stepped crack surfaces mainly characterized or accentuated by karstic forms (pavement karsts, sinkholes, etc.), peculiar sub-circular fractures pattern. Underground surveyings showed the existence of loose ore deposits, sometimes with water circulation, and abundant presence of deposits made up of iron sulphides and sulphates and suggesting a general acidic environment with continuous solution, transport and deposition of ore. Finally, some information recorded by the Bureau of Mines authority tell us more about onset, duration and techniques of mining together with the location of the main drift system and mined out ore bodies.

Therefore, the acceleration of the observed slope instability phenomenon can be imputed to the coincidence of different concomitant / collateral factors like mining (excavation and backfilling), undermining, karstic environment, pyrite solution, water pressure, main bedding and discontinuity sets orientation driving the natural slope evolution, duration of mining activity, changes in drainage, slow but continuous evolution.

As a consequence, it must be stressed out the role of anthropic exploitation in weakening the carbonatic rock mass already weaker than the granitic intrusion. In such a way gravitational stresses could have acted with increased concentration reaching a greater effectiveness in deforming the rock mass below the slope feet, triggering subsidence and coupling it with slope instability. This action, lasted probably for almost a century, could be resembled to that induced by the increase in relief energy by natural excavation of very high slopes. Eventually, successive slope movements have been probably influenced by the rapid fracture opening and the consequent change in water drainage and infiltration to charge the karstic groundwater system.

Besides, the presence of superficial brittle structure, like deep fractures with peculiar sub-circular pattern, shape and geometric characteristics (V and Λ aperture profile), is in perfect agreement with the otherwise rare observations reported in the technical literature about mining subsidence effects on overlying slopes (FORRESTER & WHITTAKER, 1976).

Anyway, one problem still arises when doing this comparison because maximum vertical displacement seems to be located in the lower third of the Mt. Calvo slope, while for FORRESTER & WHITTAKER (1976) the most probable point is near the slope crest. It can be emphasized that the study by FORRESTER & WHITTAKER examines consequences of relatively shallow undermining on colliery spoil heaps made up by loose material and then not structurally controlled, and also that the case here discussed concerns an asymmetric and irregular distribution of mining drifts and tunnel, more developed to the N and E flanks, within and outside ore bodies of irregular shape and at greater depth. This distribution could have easily guided the subsidence in a different way from the ideal one (symmetric and with regular excavations) as also suggested by some numerical simulations run to study the problem.

Numerical modelling techniques pointed out the disuniform displacements distribution along the entire slope with maxima at the slope crest and close to the ore bodies. This two maxima, well comparing with field observations, correspond also to the two sectors characterized by maximum depth of movement, ranging between 80 m and about 180 m respectively, and with maximum fracture opening (4 to 6 m) and inspected depth (20 to 30 m, visible beyond 50 m). Hence, numerical simulations helped in a better understanding of the mechanism and of the extension of the phenomenon, both uphill and downhill from the slope crest, as well as the role played by main subvertical joint sets. At the same time, it has been emphasized the deep seated gravitational instability component proper of such a process even if induced and accelerated by anthropic action. These results and field observations suggest a general mechanism similar to the one proposed by HOEK (1974; fig. 7a) and BROWN & FERGUSON's model (1979; fig. 7b) for progressive hangingwall caving. According to this models, the deep seatedness of a slope instability is a function of the depth of excavation as well as of the rock mass properties, and the size of the mass of debris formed by unstable and caved material above the excavations.

Then, what are the characteristic that distinguish a deep seated gravitational deformation or instability from a more common landslide? What about depth, gravity role, rate of development, stress concentration, karst landforms and anthropic action?

This phenomenon appears quite peculiar, classifiable with difficulty, realizing itself in a relatively short time interval (probably less than a century) but yet with peculiar

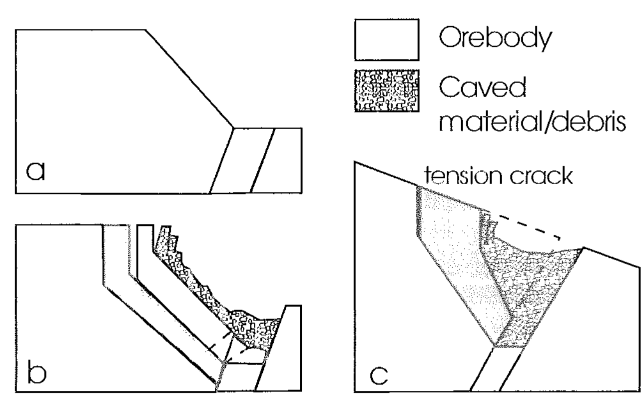


FIG. 7 - a) HOEK'S model (1974) and b) BROWN & FERGUSON's model (1979) for progressive hangingwall caving along sloping ground.

forms and resulting by combination of multiple causes and processes.

CONCLUSIONS

Environmental rehabilitation, hot and cold groundwater circulation, pollution by acid-producing rock, stability of underground mine, coupling of subsidence and slope stability are among the main problems of the Gavorrano Mining District. This paper analyses one of the possible problems related to the rehabilitation of old mining areas, that is deep seated slope instabilities as a consequence of mining induced subsidence. In fact, slope instabilities have different causes and different ways to evolve in function of many controlling factors. Such factors and causes influence also the geometry and the mechanism by which an instability occur and in this particular case they have generated a quite peculiar structure.

Subsidence induced a dragging action on the overlying slope causing sub-circular deep open fractures to develope on the E flank of Mt. Calvo. This observation is a remarkable one, not only in Italy but also in other countries, as stated by published examples (HOEK, 1974; FORRESTER & WHITTAKER, 1976a, 1976b; BROWN & FERGUSON, 1979; JONES & *alii*,1991; PELLS & *alii*, 1987) and at the same time for the notability of the evidences and the extension of the phenomenon. Therefore, deep seated gravitational instabilities find here a unique example of triggering causes, accelerating and concomitant factors and surficial indications. In the examined case, the natural slope evolution suggested by main discontinuity set orientations and by toppling and falls events sped up thanks to the prolonged undermining, presence of karstic voids and dissolution of pyritic ore.

At the same time the study of this particular phenomenon demands for a definition of deep seated deformation. What does really produce the difference between a slope instability and a deep seated gravitational deformation? According to the performed surveyings and the numerical modeling the process is quite deep (up to almost 200 m) and well developed, with an abnormal decrease of volume from surficial evidences (scarps, counterscarps, fractures, etc.) and a very small toe bulging, all happened at relatively sustained rate (within a maximum 100 years time interval) not comparable to the more commonly reported rock flow - mass creep phenomena, but still slower than most common landslides. About that, it must be emphasised that very few geological and geomorphological processes are able to modify an environment, like a rocky slope, so rapidly and for such a large amount allowing gravity to concentrate and act rapidly.

Finally, one more question rises about the possible future evolution of the phenomenon. No monitoring has been done indeed until the very last years, while absolutely no information is available relatively its onset and advance. Nevertheless, it seems sound enough that the very large openings along the slope will induce more downslope movement in the future both in the upper and at least in the intermediate slope sectors even if no more subsidence will take place. As a consequence, a more adequate monitoring would be necessary to undertake not because of risk from very fast evolution but for a better understanding of the process.

REFERENCES

ARISI ROTA F., BRONDI A., DESSAU G., FRANZINI M., MONTE AMIATA SPA, STABILIMENTO MINERARIO DEL SIELE SPA, STEA B. & VIGHI L. (1971) - *I giacimenti minerari.* In: «La Toscana Meridionale», Rend. Soc. It. Min. Petr., 27, 357-559

BARBERI F., INNOCENTI F. & RICCI C.A. (1971) - *Il magmatismo.* In: «La Toscana Meridionale», Rend. Soc. It. Min. Petr., 27, 169-210

BERTINI M., CENTAMORE E., JACOBACCI A. & NAPPI G. (1969) - *Note illustrative della Carta Geologica d'Italia. F. 127 Piombino.* Servizio Geologico d'Italia, 66 pp.

BROWN E.T. & FERGUSON G.A. (1979) - *Progressive hangingwall caving at Gath's mine, Rhodesia.* Trans. Inst. Min. Met., 88, A92-105

FORRESTER D.J. & WHITTAKER B.N. (1976a) - *Effects of mining subsidence on colliery spoil heaps - I. Mining subsidence and geotechnical aspects of spoil heaps and their foundations.* Int. Journ. Rock Mech. Min. Sc. & Geomech. Abs., 13, 113-120.

FORRESTER D.J. & WHITTAKER B.N. (1976b) - *Effects of mining subsidence on colliery spoil heaps - II. Deformational behaviour of spoil heaps during undermining.* Int. Journ. Rock Mech. Min. Sc. & Geomech. Abs., 13, 121-133.

HOEK E. (1974) - *Progressive caving induced by mining and inclined orebody.* Trans. Inst. Min. Met., 83, 133-139.

ITASCA (1993) - *UDEC: User manual* v. 2. Itasca Consulting Group, Minneapolis, USA

JONES D.B., SIDDLE H.J., REDDISH D.J. & WHITTAKER B.N. (1991) - *Landslides and undermining: slope stability interaction with mining subsidence behaviour.* Proc. 7th Int. Symp. Isrm, Aachen, 893-898.

PELLS P.J.N., BRAYBROOKE J.C., KOTZE G.P. & MONG J. (1987) - *Cliff line collapse associated with mining activities.* In «Slope instability and stabilization», Walker B. & Fell R. eds., Balkema, Rotterdam, 359-385.

SAMMARCO O. (1995) - *Geometria ed idrogeologia di reti minerarie quali fattori che limitano o favoriscono il riutilizzo di miniere abbandonate.* L'Industria Mineraria, 16, 5, 14-20.