A Case of Induced Subsidence for Extraction of Salt by Hydrosolution

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ABSTRACT In the commune of Belvedere (Calabria, Italy), at a depth varying from 200 to 600 m, lies a mine of rock salt. The layers are intercalated by an evaporitic formation of Messinian Age, trasgressively covered by Plio-Pleistocene sandy clayey deposits. Since 1970, the salt has been extracted by hydrosolution, which caused subterranean cavities inducing a wide subsidence. From the beginning the extraction was worked out by the "multiple wells" method, which didn't allow a safe control of the forming of dissolution cavities. The subsidence caused collapses (sinkholes, landsliding, etc.). Presently, extraction methods that have a more concern for the environment ("single wells") are used. The National Geological Survey is checking the mining area from a geological point of view and is looking after the subsidence.

GEOLOGICAL AND MINING SITUATION OF BELVEDERE SPINELLO ROCK SALT MINE

The evaporitic formation of Messinian Age in the "Crotonese Basin" (Calabria - Southern Italy) has intercalations of salt bed. It's trasgressively covered with sandy-clayey deposits of the Plio-Pleistocene period. In the commune of Belvedere Spinello, on the left side of Neto River, locality Timpa del Salto, lies a rock salt mine, useful from an industrial point of view, exploited since 1970 (Figs. 1 and 2).

The mine consists of two main salt layers, one of which, the first, is exploited; it is made up of breccia (clayey marl, gypsum, etc.), cemented by salts; it has a mineral percentage of about 60 and an average thickness of about 150 m. The depth from the ground level of the surface of this layer varies from 200 to 600 m.

The salt layers are overhung by an alternance of clays and gypses; they are folded and create an anticline with the axe oriented from NNE to SSW.

Three faults run parallel to the axe: Timpa del Salto, oriented from North to South and the two faults of Serra Filetto and TS 3-TS 4,
FIG. 1 Field brine geological map.

oriented from NNE to SSW.

The anticline is asymmetrical; its western side is vertical, or locally overturned, and the eastern side degrades eastward with an inclination of 15-20°.

The salt in the mine is schistose, and this indicates a plastic deformation with a vertical component, so that the mine looks like an incipient diapir.
THE EXTRACTION METHODS IN BELVEDERE SPINELLO MINE

A quantity of mineral was estimated in about 250 millions of tons of sodium chloride.

The mine is connected to the refinement plant of Cirò Marina by the pipe-line. Here, the brine is purified, the salt recrystallized and shipped to the chemical plants of Porto Marghera (Venice).

From the beginning of the activity of Belvedere Spinello the concessionary company adopted the method of multiple wells. It consists with the introduction in a borehole of fresh water under a pressure of 200 atmospheres, to gain the solution of the salt layers (hydrofracturing) and the connection with another well. The production is allowed using a pressure of 25–30 atmospheres and the salty solution, called brine, goes up to the surface, beginning a continuous productive cycle.

The company used this method until 1984, when a lot of environmental problems arose.

In 1987, when the mining activity restarted, the company adopted a program of gradual passage from multiple to single wells, in which
the descending column of fresh water and the reascending one of the
brine can be in coaxial tubes inside the well itself.

The activity of the mine is concentrated on two allined zones
called "North basin" and "South basin".

From the beginning of mining, more than forty wells were opened,
fifteen of which are active, with a production of about 300 m³/hour of
brine and 300 g/l of NaCl.

THE SUBTERRANEAN CAVITIES CREATED AFTER THE EXPLOITATION

On account of the described method of exploitation, subterranean
cavities formed and replaced the salt and the insolubles mixed with
it: moreover, such wastes remained underground, deposited on the
bottom of the cavity.

The original condition of the subsoil and the conditions after 15
years of exploitation, as results from a geoelectrical prospecting
carried out in 1984 by electrical vertical drillings, are shown in
Fig. 3.

The creation of cavities caused quick subsidence and "sinkholes".
Moreover, the subsidence was foreseen as a phenomenon connected with
this mining method.

The geoelectrical prospecting carried out in 1984 allowed the
rebuilding of the first salt layer's roof and of dissolution and
saturation zones. The results permitted the location of the hazard
zones in the brine field, summarized in a map. The zones with higher
hazard are those with higher subsidence and microysmic intensity.

A general valuation can be done of the existing subterranean
cavities, considering the content of extracted salt, the grade, the
total outer subsidence volume and the sinkholes.

The water injected in the wells during the exploitation by
multiple wells reached a volume of about 34 Mm³, to which corresponded
a quantity of extracted salt of 12 millions of tons, with a specific
weight of the undisturbed material of 2.16 t/m³, that is 5.5 Mm³.

Since the weight of the average grade of the salt is about 60% in
NaCl, nearly 8 millions of tons of insolubles deposited on the bottom
of the subterranean cavities have been removed during the dissolution
process. We can consider as specific weight of the removed wastes
2.455 t/m³; we have therefore a volume of the undisturbed material of
3.3 Mm³, that is 5.2 Mm³ of refilling, taking into account a rising of
volume of 1.6.

The outer subsidence caused a sinking of 640,000 m³, with a
consequent refilling of about 0.8 Mm³, considering with prudence a
coefficient of rising volume of 1.3 (in fact it's not certain that the
roof of the cavities in its whole will break).

The three sinkholes caused a subterranean refilling of about 2
Mm³.
Induced subsidence for extraction of salt by hydrosolution

**Fig. 3a** represents terrain original condition, before mining. Terrains are divided into 3 resistivity classes ($p$ by ohm·m):

- $p > 50$ salt ore body
- $50 > p > 2$ cover terrains
- $p < 2$ very conductive terrains (clays)

**Fig. 3b and 3c** represents brine field condition at 1984, after 15 years mining. Terrains are divided into 3 resistivity classes:

- $p > 50$ materials remained of original salt ore body
- $50 > p > 2$ cover terrains
- $p < 2$ very conductive terrains, defined as "impregnated masses" and consisting of: terrains in which circulate brine, terrains liquefied and re-deposited on the bottom of solution cavities (insolubles), brine ($p = 0.08$ ohm·m)

**FIG. 3** Brine field profiles as regards the electrical resistivity (source: Mining Italia, 1985).
Summarizing, we have a volume of residual subterranean cavities of about 0.8 millions of m$^3$.

Some of these spaces are marginal, with limited dimensions, disconnected to the main structure of the cavities, out of the area of subsidence, so probably they will not be filled, but remain fix because of the pillars.

SUBSIDENCE CAUSED BY EXTRACTION AND CONSEQUENT EFFECTS

The most remarkable lowerings have been surveyed in the North basin, where the exploitation was mainly concentrated. The other productive zones are less concerned by the subsidence.

The concessionary company ordered topographic levellings to follow the evolution of the subsidence, starting from October 1980; at present, the National Geological Survey carries out two levellings a year.

The first measurements, though made on a topographic surface already influenced by previous exploitations, are the reference for the following ones.

The subsidence in its hole shows a main depression in the North basin (Fig. 4). In detail, the main depression corresponds to the sinkholes n. 1 and 3.

The levelling measurements show a general increase of the subsidence values respect to the previous data, reaching values of more than 90 cm in the North basin, in a round area with the barycentre in the well TS 13; notice that the two sinkholes of the North basin are less than 100 m away from the well TS 13. The average speed of the subsidence in this limited area is 12 cm per year. At present, a decreasing course of these values (3-4 mm/month) is noticed.

Also in the South basin on the right of Fosso Barretta, another subsidence cone occurred.

In the course of the mining, the exploited cavities came in touch with faults at least three times. As a consequence, emissions of water, close to the zone of "Barretta" and East of the Timpa del Salto fault, have been noticed, during the hard works of hydraulic connection between the multiple wells TS 3 and TS 4.

All this shows the remarkable difficulties to control the extending of cavities and the development of destabilizing stresses caused by the multiple wells, with the widening or forming of fractures through which the brine may flow, even a long way from the wells to connect.

The main effects caused by the subsidence were the sinkholes, wide and deep subcircular depressions with subvertical walls opening in the ground.

These collapse cylinders are characterized by the lack of
macroscopic concentric superficial fractures, often observed in sliding phenomena.

The first sinkhole occurred around the well TS 5 in January 1983. After the collapse, a round abyss opened in the ground, with a diameter of 50 m and an area of about 2000 m², filled with brine.
Presently, the depth of the lake is about 6 m, the continuous erosion of the walls causing the progressive refilling of the abyss itself.

The estimated volume of such mass of water is about 20,000 m$^3$. The salinity is 30 g/l of NaCl.

The second sinkhole revealed itself in April 1984, on the right of Fosso Barretta, south-western edge of the brine field. It occurred on the foot of a hilly slope, causing the sliding of a terrain in the lake of the sinkhole itself, with consequent violent expulsion and projections of a huge mass of brine.

A volume of about 100,000 m$^3$ of brine produced a flood, first in the river bed of Fosso Barretta, then in the plain of Neto River, extending through an area about 120 hectares wide. The brine moved straight to the fluvial stream of Neto River, polluting it, and also polluting the local ground waters by percolation.

The sinkhole was formed along the fault of Timpa del Salto, joining the "Marly clay of Cutro" (that suffered the sliding), downstream, to the "Molasse of Scandale", upstream.

The landsliding material has a volumetric consistence lower than the landsliding body; this means that the missing rock filled the sinkhole because of the collapse of the roof of a subterranean cavity.

The barycentre of the collapsed block isn't placed on the vertical of any productive wells; migrations of brine, causing hollows, may therefore occur, even in zones far from the injection well, or far from the reflow well.

After the landslide and the consequent flood, the works were interrupted and began again in the first months of 1987.

A direct effect of the described phenomenon was the saline pollution of waters. The salinity of fluvial waters, after the flood of brine, reached values of 19.7 g/l. Step by step, the salinity has then returned to normal values; in that interval, the salt made the waters completely unusable for any purpose.

The ground waters of alluvial fill of Neto River, the most important of the zone, are placed at an absolute elevation of about 20-30 m. The brine in the dissolution cavities should be instead placed at a maximum elevation of −200 m and thus it shouldn't pollute the ground waters of the alluvial fill, being deeper.

In fact, the complexity of the circulating brine in the mining basin allows one to believe that in some strict areas it may be placed at an elevation higher than the replaced salt, as shown by the sinkholes with expulsion or emerging of brine.

The third sinkhole formed in September 1986, in the area of Barretta Asciutta, North basin, inside the triangle whose vertexes are the wells 13, 10 and 7, at an elevation of 120/130, on a quite steep hilly slope.

This new abyss is about 200 m away from the first sinkhole, the one close to the well TS5.

The concerned terrains are the "Marly Clays of Cutro". In the
beginning, the diameter of the hole was about 30 m: the bottom of the abyss was made of a small brine lake and the depth of the surface of this water body was about 20 m below the hole mouth. The width of the sinkhole has increased because of the subsequent collapses, the brine dispersed underground and, at present, the diameter of the hole is about 50 m, with an area of about 8,000 m². The depth is about 25 m.

As observed in field, and as results from scientific literature, these sinkholes are the consequence of a quick subsidence area caused by the extraction of salt.

CURRENT METHODS OF EXTRACTION

On account of the disastrous events caused by the multiple wells, in the last years this method was given up and now the extraction is
worked only by single wells.

Presently, the plan of mining activity is to control strictly the development of subterranean cavities caused by the dissolution, so that the induced subsidence can be avoided. That's why the cavities are created with programmed dimensions, with a diameter of 70 m and a height of 50-150 m depending on the characteristics of salt, separated by pillars so strong to support the "slab" of brine substaning the covering clays. The dimensions of cavities are yearly checked by the Sonar Survey and daily by a geometric model "cavita" set on computer. In other words, we adopt the method by "chambers and pillars", fit to the particular mining (Figs 5 and 6).

CONCLUSIONS

In the described geological situation, the most induced subsidence occurs where the following two geological conditions happen: a) maximum height of the salt roof; b) minimum thickness of the Plio-Pleistocene cover of the brine field.

To these geological factors is added the anthropic ones: the maximum exploitation of the mine.

The sinkholes n. 1 and 3, identified on figures, are placed in correspondence of the bend of the anticline and of the zone of highest subsidence.

The faults are also very important, creating preferential ways for the circulation of subterranean waters and the brine, particularly where the latter is subject to the high pressures of injection of the
fresh water, required for the hydrofracturing in the multiple wells. The subsidence continues in the mining zone slower than in the past. At the moment, it's difficult to make hypotheses about the time necessary to stop the phenomenon.

REFERENCES


