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Monitoring Environmental Impact in the Belvedere Spinello Brinefield (Italy)

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ABSTRACT

The Timpa del Salto rock salt deposit is located on the western limits of the Crotonese Neogenic Basin in Calabria (Italy) and a brinefield has been operating near Belvedere Spinello town since December 1970. Salt was extracted by solution mining using a multiple-well method with several hydraulically interconnected boreholes. The operations created large underground cavities and a fairly large area of subsidence and some sinkholes appeared on the surface. The multiple-well method was therefore abandoned in favour of a single-well technique in 1987–88, and all mining activity is at present carried out using single boreholes.

To maximize security of mining operations in the new brinefield and to protect the environment in the old one, the mining company has implemented several control systems, including: computer-aided continual monitoring of the new cavities, continuous monitoring of micro-seismic activity induced by mining operations, geoelectric surveys to control variations in underground resistivity as a result of brine infiltrations, geodetic levelling to monitor subsidence, gravimetrics, monitoring of hill slope stability, monitoring of water-table levels and water characteristics.

INTRODUCTION

The Timpa del Salto rocksalt deposit lies on the western limits of the Crotonese Neogenic Basin, beside the Ionian Sea in Calabria (Italy) (Roda, 1965; Bossio et al., 1979; Roda, 1984). The brinefield is near Belvedere Spinello town. Salt extraction by solution mining began in December 1970, using a multiple-well method with several hydraulically interconnected boreholes. On average, 12–14 wells were always operating, producing about 400 m^3/h of brine containing 300 g/l of NaCl daily. Annual salt output was about 1 M t. Practically the whole saltbed at depths of 300–500 m was leached out, with uncontrolled formation of large underground cavities. As the overburden rocks are mostly clays with practically no bearing capacity, a process of gradual continuous sagging began, resulting in a fairly wide area of subsidence (max. 1 m) and 3 sinkholes.

Currently, all mining activity is by single boreholes in the south-east part of the deposit. To maximize safety in the new brinefield, a series of control systems, including computer-aided continuous monitoring of cavity evolution, was installed to monitor micro-seismic activity, evolution of subsidence, stability of hill slopes, and variations both of water-table levels and the characteristics of surface and subsurface water (Cecchi, 1976; MINING, 1985; K.B.B., 1988; Guarascio et al., 1989a,b, 1990; Montecatini, 1990).

COMPUTER-AIDED CONTINUOUS MONITORING OF NEW CAVITIES

Cavity shape is systematically monitored by mine technicians using a mathematical model ("Modello Cavità") specially developed for solution mining by single boreholes and installed on the mine's PC (Dussaud et al., 1990). Cavity shape and size are also verified yearly by means of a sonar survey within the boreholes. In single-borehole solution mining, the liquid (water or unsaturated brine) is pumped into the cavity through a tube and the solution containing the dissolved salt is extracted through a second tube either inside or outside the first one. The elevation of the point of injection can be higher or lower than the extraction point. The first case refers to the so-called "inverse" method (injection through the outer tube or "casing" and extraction through the inner one or "tubing) whereas the second refers to the "direct" method (injection through the tubing; extraction through the casing). Vertical variations of NaCl grade are measured using geophysical logs of the boreholes. Barren material remains inside the cavity and its volume expands as a result of comminution and waterlogging.

The model is based solely on data collected during normal mining activity steps and simple geometrical hypotheses. The production parameters are as follows:

- elevation of liquid injection point,
- weight of the NaCl extracted during the step,
- elevation of cavity ceiling at the end of the step,
- salt grade recorded during the step (measured automatically by the programme on the basis of the geophysical logs).

The geometrical hypotheses are the following:

- a cavity will be symmetrical with respect to the borehole axis,
- salt solution velocity will not be affected by the distance between cavity wall and injection point,
- barren material will fall to the bottom of the cavity (sump) forming a horizontal layer below which leaching is no longer possible.

The current version of the model can start with any cavity shape provided by the user. The results are visualized on the display, printed or memorized to file. The technicians use the model constantly to verify that the cavity is behaving as predicted by mine design and cavity shape and size are verified annually by sonar survey (Prakla, 1991).

The measurements are made using an echolog. A probe with an ultrasonic transmitter-receiver is introduced into the borehole. Its tip is equipped with two ultrasonic transducers, one of which rotates vertically while the other one rotates horizontally: a magnetic compass in the measuring head regulates its orientation in plan. A computer controls the measuring process, imposing regular periods and recording the data. The latter are displayed on a colour screen on an X–Y graph of the polar coordinates with origin at the magnetic pole. 3D images of the horizontal and vertical sections are then printed.

Two surveys at the beginning of the years 1990 and 1991 have been carried out in the 15 active single boreholes, generating 24 vertical sections of each cavity. Cavity shapes are never symmetrical, mainly because of the variability of the presence of barren strata within the saltbed. As the current version of the model handles only symmetrical shapes, the data recorded in 1990 were used to compute an average section that was input to the model as the starting point for predicting cavity evolution during one year of mining operations under the design parameters. The aim was to compare the model's predictions with the measurements to be made during the 1991 sonar survey. Figure 1 referring to a typical case indicates that the result is satisfactory.

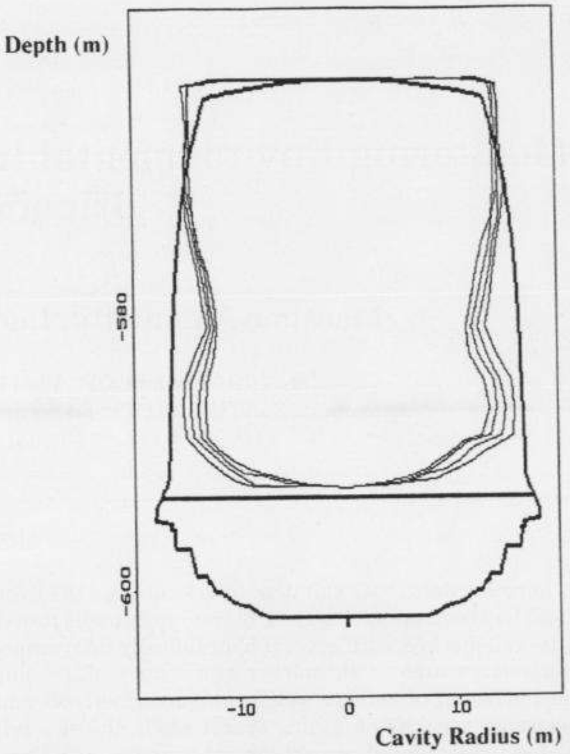

Fig. 1. Belvedere Spinello Mine, TS41 cavity. Comparison between sonar surveys and the CAVITA model.

A revised version of the model is being developed to handle non-symmetrical cavities on the basis of measured sections, also allowing the user to select the angle of depositing of barren material on the cavity floor. The new model should be more realistic in taking account of cavity formation in saltbeds where salt-bearing and barren strata vary as at Belvedere Spinello.

Thanks to Modello Cavità and the annual sonar surveys, it has been possible to monitor cavity development; cavity shapes and sizes have thus been maintained fairly close to the requirements of the mine design thereby ensuring a high level of safety of mining operations.

CONTINUOUS MONITORING OF MICRO-SEISMIC ACTIVITY INDUCED BY SOLUTION MINING

Elastic energy liberation can occur in the rocks around a cavity formed by solution mining, possibly with more or less localized collapsing. In fact, the stresses in the rocks that form the cavity walls or ceiling may exceed mechanical strength giving rise to dynamic phenomena in the form of vibrations. By monitoring micro-seismic activity as the cavity expands, it is possible to follow cavity development and pinpoint the onset of any undesirable events (Guarascio, 1986; Fiore et al., 1989).

For this purpose, a recording network was installed to capture and analyze subsurface vibrations. The system for recording and processing seismic signals comprises 12 peripheral units (PU) connected by radio with a computer at the recording centre or concentrator. Each PU has a geophone and equipment to process and transmit the signals and is powered by solar cells. The concentrator is equipped to receive and process incoming signals and interconnections are controlled by a PC.

The geophones at ground level detect subsurface seismic signals and generate an electrical impulse with the corresponding amplitude, frequency and duration. These are sent to the PU which examines and memorizes them. If amplitude and frequency satisfy pre-established conditions, the concentrator is alerted. If more than five PUs send warnings within an established period of time, the concentrator enters a state of alarm, orders the PUs to transmit the signals that prompted the alerts, verifies them then sends the data to the PC for analysis and memorization.

The geophones are standard uni-directional accelerometers with frequencies of around 10–500 Hz, which have been modified by adding an analogical signal amplifier with a frequency regulation band.

Each PU comprises a digital analog convertor that digitizes the signals captured by its geophone. The sampling period of 1 msec is based on the frequency of the seismic signals to be recorded. With an installed memory (RAM) of 512 Kbytes, a PU can store about 8.5 minutes of a "history" of events. The PU is linked with the concentrator by modem and a radio with a frequency of about 450 MHz. It is run by a microprocessor whose software is contained in an EPROM.

The task of the concentrator is to receive signals from the PUs and send them (by cable) to the PC for processing. It is operated by a microprocessor whose control software is memorized on an EPROM. The PC is a PC-AT IBM compatible with a 40 Mbyte hard disk and software for receiving, preprocessing and memorizing the data.

The memorized data are processed off line as follows:

– the recorded data are filtered using appropriate software to eliminate spurious events,

– the filtered data are automatically analyzed and a summary file of seismic activity by month is generated showing the period, amplitude and energy that characterise each recorded event, these parameters are processed stabilistically, paying special attention to evolution over time and the spatial distribution of the recorded event,

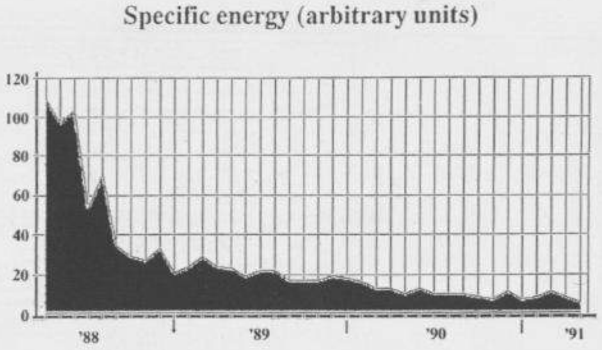

Fig. 2. Belvedere Spinello Mine. Microseismic network activity (April 1988–May 1991).

– the data base is updated on the basis of the latest results,

– the results are graphically represented and interpreted.

A computer procedure was also developed for automatic determination of the epicentre of events but it cannot yet be used since a satisfactory seismic model of the zone is lacking.

Figure 2 illustrates an analysis that highlights the behaviour of the specific energy vs time of the recorded events. This behaviour evidently followed a declining trend until recently, when it gradually became constant. This can safely be attributed to the fact that mining operations are being carried on with single boreholes only, permitting a fairly precise control of cavity formation.

The hardware of the recording system is currently being upgraded by incorporating the latest instrumentation. The software will also need to be revised although the same functions shall be maintained.

GEOELECTRIC SURVEYS TO MONITOR UNDERGROUND RESISTIVITY

Geoelectric surveys have proven to be an effective tool for monitoring the cavities created during solution mining. During two surveys, in 1985 and 1991, respectively, 77 vertical resistivity soundings were carried out with maximum AB/2 between 2000 and 4000 m, on the same positions and using the same names (CMP, 1985; CMP, 1991).

The method is effective when applied to subhorizontally stratified rock formations with sharply differentiated resistivities, certainly not the case at Belvedere Spinello, where geoelectrical properties

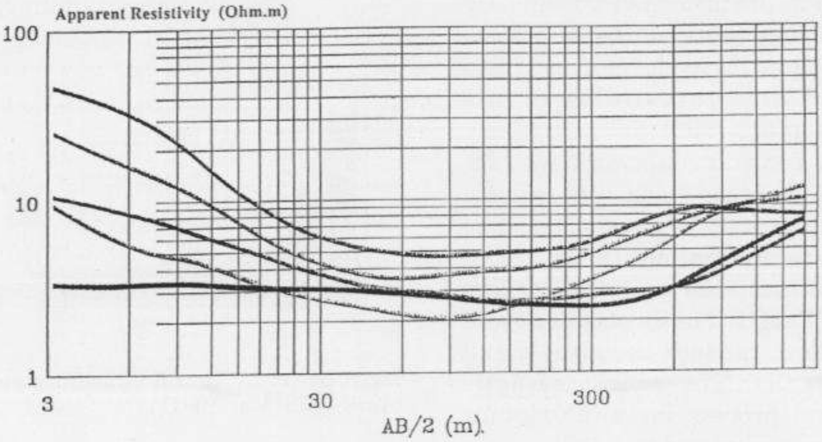

Fig. 3. Belvedere Spinello Mine. Cluster analysis results.

differ only slightly. The curves were therefore interpreted using Koefoed's direct method (Koefoed, 1979), also taking account of the data from mechanical drillings. The interpretations were also correlated with the topography and selected production aspects to eliminate possible ambiguities.

The cavities formed by solution mining are partly filled by a mixture of insolubles and detritus from cavity ceiling and walls, all waterlogged with brine. As brine has a significantly lower resistivity than rocks, geoelectrical measurements can reveal the physical effects of mining operations by identifying horizons of higher conductivity that were not present in the original situation. The lowest resistivity of rock formations being 2 ohm-m, any area with a lower value is likely to coincide with circulations of brine: e.g. a cavity created by solution mining of a saltbed. The 1991 geoelectric survey aimed at detecting such areas with a view to correlating them with the 1985 data and with the status of mining operations.

The concept of vulnerability as numerically expressed by the "risk" parameter applies to the resistivity horizons but it is not a mechanical concept like a safety coefficient. Whereas the former evaluates a situation in numerical terms, relating it to a preceding situation or data from other places, without providing an absolute value for risk, the latter is generally the ratio between the present situation and a future situation when the structure is expected to collapse. As a numerical value for the risk of sinkhole formation is not known, this parameter can never be used as an absolute value.

The method used to calculate the risk coefficient involves the calculation of 3 partial coefficients. The first (C1) is based on groups or "clusters" of resistivity soundings, the second (C2) considers the soundings individually, and the third (C3) compares the geoelectrical and geostatistical data. The resulting risk coefficient is used both to make the data consistent and to consider several aspects of the same phenomenon.

A relation can be defined for quantifying the risk in a given point of lower resistivity: that risk is:

– directly proportional to the thickness of the salt bed,

– inversely proportional to its depth,

– inversely proportional to the resistivity: the lower this value, the greater the probability of leaching of presence of brine.

To calculate C1, the soundings are divided into homogeneous groups on the basis of the curves based on field measurements, and non-hierarchical cluster analysis (Howard, 1983) is applied. The specially developed calculation code detects these "subjects" (the measured curves) by minimizing variances and ensuring that distances between the clusters are the maximum. The final classification is obtained by comparing each subject with the midpoint of the groups (Euclidean distance from the vector of the arithmetic means). Figure 3 illustrates the result of this analysis, showing the characteristic curves of each identified group. Each group thus obtained is then interpreted using the same Koefoed direct method. The described procedure provides the basis for dividing the brinefield into zones with similar geoelectrical properties and a computed risk coefficient. Every sounding is thus associated with a cluster and the related risk coefficient.

To calculate C2, the measured curves are interpreted individually using the same direct method. Figure 4 shows an example of such interpretation. These curves are then used to calculate C2 as described above, except that only areas where resistivity is lower than 2 ohm-m are considered. The procedure adopted in 1985 produces maps that highlight the evolution over time of the low resistivity zones.

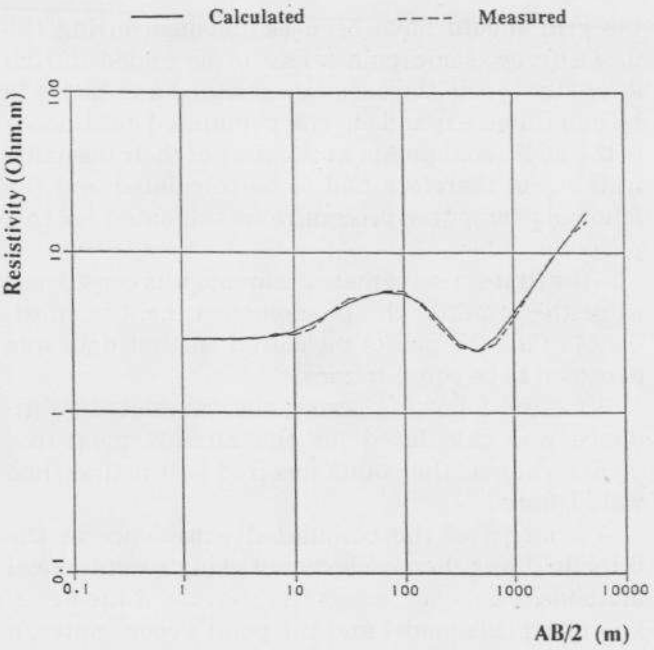

Fig. 4. Belvedere Spinello Mine. S30 sounding.

The distance between the elevation of the hanging wall of the first saltbed (as detected by a geostatistical analysis based on mechanical drillings) and the elevations of the hanging wall of the basement rock (as detected by geophysical measurements) is the basis for defining C3. In fact, solution mining and the corresponding cavities are present if the higher resistance is found below the salt horizon. On the other hand, if the higher resistivity is above the salt horizon, the footwall of the overburden formation evidently comprises mainly resistant components like evaporitic formations with weak clay matrices, lithoid components of the pleo-pleistocenic complex.

The values generated by the above risk analysis have no meaning if extrapolated from mining operations. No conclusions of any kind can be based on geophysical measurements alone. Other factors must be taken into account. In the present case, the risk maps were correlated with the topography, the positions of the boreholes, and the thickness and properties of the saltbed.

Comparison of the data for 1985 and 1991 is facilitated by dividing the absolute values of the risk coefficient by the maximum value obtained in 1985, whereas the present situation, examined in isolation, can be analyzed using the maximum 1991 value as the denominator. In practice, since the two maximums are virtually the same, the two maps do not differ very much. Figures 5 and 6 are the risk maps. The 1985 data, which had been interpolated manually, were reprocessed with a view to comparing the two analyses with the same computerized interpolation method. Figure 5 illustrates the relative values obtained by normalizing the risk coefficient. A clear reduction of vulnerability in the N zone can be attributed to settling along a sinkhole that appeared after 1985. The area that was fenced off due to brine seepages is not detected, probably because the phenomenon that has or will soon occur cannot be detected by the degree of detail offered by this method. On the contrary, a geophysical detailed analysis conducted using SEO rectangles confirmed the high risk of the zone and hence the need to take safety precautions.

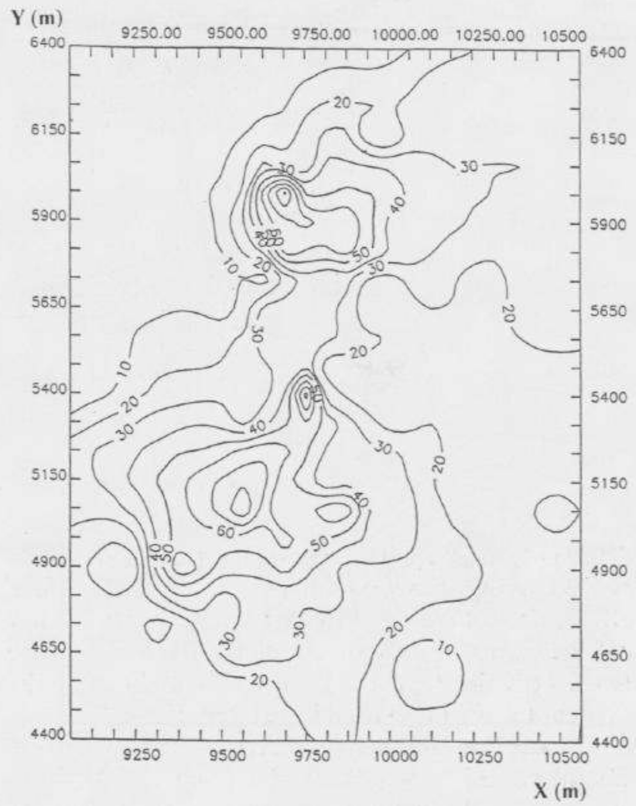

Fig. 5. Belvedere Spinello Mine. Risk analysis percentage values, 1985.

Figure 6 shows the maximum risk value calculated in 1991. Comparison with the same 1985 value provides a fairly optimistic picture for the N and central zones but the situation clearly worsens with regard to the zone between the old and new brinefields. However, this zone is not minable and the phenomenon can be considered stable. Finally, the higher risk coefficient of the new brinefield is not a cause for concern; all cavity shapes are compatible with the design and are not connected: the calculated coefficient translates only the normal mining phases.

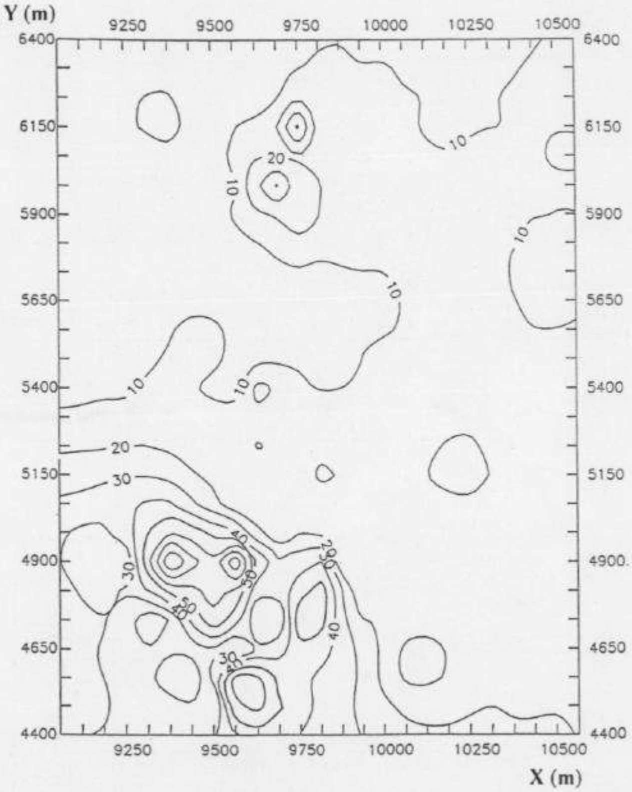

Fig. 6. Belvedere Spinello Mine. Risk analysis percentage values 1991. (Referred to 1985).

GEODETIC LEVELLING TO MONITOR SUBSIDENCE

Subsidence due to solution mining in this brinefield has been monitored since 1980. During 21 surveys, a total of 223 measurements have been made at the same benchmarks.

To evaluate subsidence, the elevation of a point is measured (with reference to a permanent benchmark) appropriately constructed to reflect only sagging phenomena, i.e. ignoring any phenomena due to other, mostly seasonal causes that may affect surface ground level. In the present case focusing on subsurface cavity formation, elevations can only drop or remain constant: any rises must be attributed to surface phenomena rather than the underground ones being monitored during mining operations. The benchmarks should therefore be built using appropriate techniques and to a depth of about 10 m. Although this could not be done at Belvedere Spinello, the results obtained were satisfactory.

The elevations were measured both by the National Geological Service and a private company. The cumulated subsidence expressed in mm was calculated for each point. Although all the points of the grid should have been established during the first survey, some points had to be added during later surveys as the area being mined and hence to be monitored expanded. The cumulated subsidence of the additional points at the time of their insertion in the grid therefore had to be calculated and the following computer procedure was adopted for this purpose:

- the first series of measurements was considered to be the origin of the phenomenon, i.e. the subsidence of all the points measured on that date was assumed to be equal to zero,
- for the following series, the cumulated subsidence was calculated for the already measured points whereas the points inserted for the first time were ignored,
- a model of the cumulated subsidence in the brinefield was then constructed using geostatistical methods,
- using this model and the point's coordinates, a value for the cumulated subsidence of each new point was interpolated,
- this value was attributed to the new point and the latter,
- from that moment on, is considered to be fully integrated with the network as though it had been part of the first series.

It should be noted that the above methodology is conditioned both by the phenomenon itself (i.e. the extent to which the subsidence of a point can be correlated with that of nearby points) and by the algorithms and parameters used to construct the model. The described method provided a body of homogeneous (i.e. clarified) data as the basis for analyzing the events affecting single benchmarks and/or the whole territory they cover.

The data on individual benchmarks were analyzed by drawing the curves of subsidence as a function of time. It was therefore possible not only to correct measurement or recording errors by checking any anomalous behaviours; but also to observe the behaviour of some of the characteristic points under the impact of known events, e.g. the appearance of sinkholes. The curves of certain points near to the sinkholes are illustrated in Fig. 7.

This analysis indicates (see the dates of two sinkholes in Fig. 7) that the subsidence increased only after the event and not before it. Measurements of subsidence cannot therefore be used as a precursor of sinkhole formation.

To analyze the behaviour of subsidence on the whole brinefield, it was necessary to build a model of the phenomenon and draw a contour to illustrate the results. This was done both for cumulated subsidence and for variations of subsidence over time.

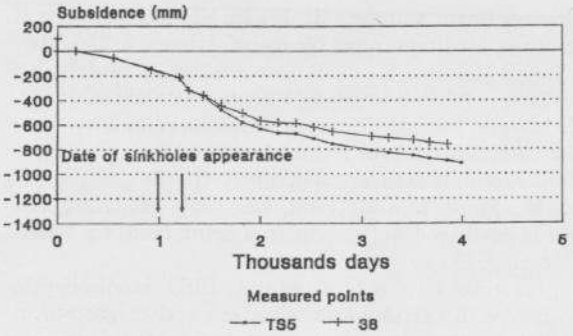

Fig. 7. Belvedere Spinello Mine. Subsidence vs. time.

Figure 8 shows that subsidence is significantly greater in the area that had been mined using the multiple-well method (the north part) than in the S parts where salt is being extracted using single boreholes.

CONTROL OF HILL SLOPE STABILITY

Four inclinometric wells were installed for periodic measurements of hill slope stability. Ten recordings were made in three years in the two which are located on either side of the landslide caused by a sinkhole (the first measurement serving as reference for the following ones). No significant movements have been detected since the instrument heads have shifted less than 25 mm with respect to their opposite extremity situated at about 100 m depth.

Inclinometric tubes were installed in the other two wells whose purpose is to monitor any movements under the nearby town of Belvedere Spinello. Seven recordings were made in 6 months, the first one serving as the reference for the following ones. No appreciable evidence of shifting has been recorded as the instrument heads have shifted less than 8 mm with respect to the opposite extremity.

GRAVIMETRY

Two micro-gravimetric networks exist in the area, one of which focuses essentially on the brinefield whereas the other covers a significantly wider area. The purpose of the former is twofold: to detect any spatial variations in gravity accelerations so that an attempt can be made to correlate them with the existing underground cavities, and to evaluate, by repeated measurements made on the surveillance network, any variations of the measured values that can be correlated with mining activity. The second series of gravimetric measurements carried out in April 1989 did not detect significant differences with respect to the preceding campaign.

The second network covers the area of Belvedere Spinello town as well as the areas surrounding the brinefield. Measurements are repeated annually, when high precision levelling is carried out, in order to try to correlate any variations in gravity acceleration with altimetric accelerations. The aim is to detect any redistributions of underground masses whose effects are greater than instrumental resolution.

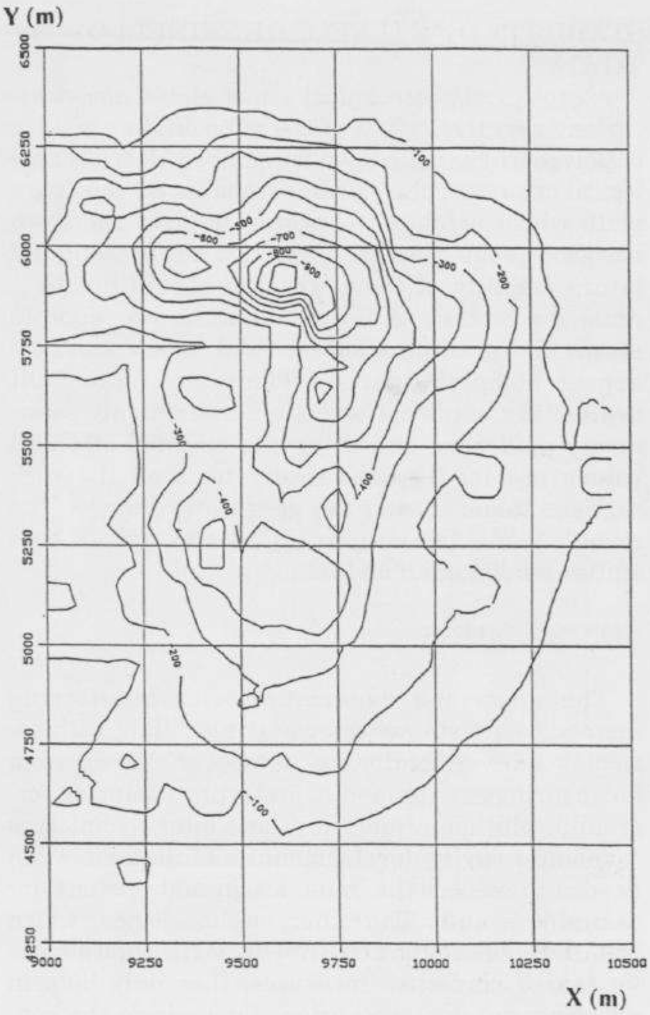

Fig. 8. Belvedere Spinello Mine. Subsidence (mm), October 1991.

CHEMICAL ANALYSIS OF SURFACE WATERS

The National Chemical Service was engaged to carry out a thorough analysis of the quality of surface waters. Several sampling campaigns were conducted covering an appropriately large area. All the findings were within normal values. The Geological Service of the Ministry of the Environment is conducting an in-depth hydrogeological study of the area with detailed chemical analysis of water characteristics.

STABILITY OF BELVEDERE SPINELLO TOWN

A geological/geotechnical study aimed at detecting any negative effects of the mine on the stability of Belvedere Spinello town found no evidence of geological or geomorphological instability. As the Zinga plate which extends westwards towards the town has good geomechanical properties, the present and future stability of the town area should not be a cause for concern. A further analysis was done to assess the possible effects should a new sinkhole appear along the part of Timpa del Salto fault nearest to the town. Conducted under highly pessimistic conditions and using the minimal strength values provided by laboratory tests on the rock samples taken during the geognostic surveys, the results point are entirely reassuring under both static and dynamic conditions.

CONCLUSIONS

The described experience with monitoring methodologies shows that cavity modelling with periodic sonar verifications is the most effective system for ensuring environmental protection during underground solution mining. It allows mine technicians to monitor cavity development and intervene when needed to respect the mine design and prevent undesirable events. The other methodologies, which ensure an *a posteriori* control, do not provide a basis for taking corrective measures; they only help in adopting suitable precautions for limiting the consequences.

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