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GEOMECHANICAL EFFECTS OF OPERATION AND CLOSING THE IDRIJA MERCURY MINE ON THE ENVIRONMENT

Jakob LIKAR

University of Ljubljana, Faculty of Natural Sciences and Engineering, Aškerčeva 12, 1000 Ljubljana, Slovania
Corresponding author's e-mail: jakob.likar@ogr.ntf.uni-lj.si

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ABSTRACT
The past five centuries of the Idrija Mercury Mine's operation have had consequences on the environment, which have directly influenced the deformations developing in the wider exploration area. During the many years of mercury ore exploitation, the cross-stope mining method with backfilling from bottom to top was used. This has strongly transformed the stress-strain field in the surrounding rocks and caused long-term deformation processes that are still in progress. This is because the deformations have a small time gradient and thus bigger breaks or faster sliding terrain above old mine workings are not expected. The surface movements are bigger in the area built of Permian-Carboniferous, low-bearing-capacity rocks, which in the past was destroyed by major tectonic movements in the rock structure. Mine closure works, which included grouting and hardening of destroyed underground areas, as well as filling parts of the mine and backfilling empty spaces (i.e., mine roadways, blind shafts), are finished. The efficiency of mine shutdown works is constantly being verified by means of geotechnical and other measurements and observations, and will continue in the future.

KEYWORDS: Mercury Mine, cross-stope mining method, backfilling, sublevel mining method with consolidated backfill, low bearing capacity rock structure, geotechnical measurement.

1. INTRODUCTION

The Idrija Mercury Mine has caused extensive deformations in the wider mining area in the last five centuries. The mine closure works were finished, but various observations and measurements in the mine and on the surface above the mine are still active, because the time-dependent deformation processes in the wider area were not finished. The measurements are conducted in the prescribed time intervals twice a year in order to ensure the monitoring of deformation processes. The results of measurements and observations give a realistic insight into the actual occurrences, which also enables verification of the effects of consolidated and backfilling works in the mine.

Time-dependent processes which are closely linked to the extent of ore exploitation and the type of mining methods, which were used in the past, and in particular to the geological and geomechanical conditions, are still present. That process is present particularly on the ground surface above Permian-Carboniferous layers and other low-bearing-capacity ground layers. The main goal of mine closure works is the final stabilization of the area which will be able to use land for new construction projects. Figure 1 has shown complex mine structure developed below the town Idrija.

2. GEOLOGICAL AND HYDROGEOLOGICAL INTERPRETATION OF THE WIDER MERCURY MINE AREA

The mercury ore deposit which is 1500 m long and 300-600 m wide, extends in the directions northwest and southeast, and has a depth of the ore-bearing zone at about 450 m. The deposit was open in mine history by entrance gallery and vertical shafts. The deepest shaft which is now entirely closed with concrete backfill, reached a depth of 420 m at approx. 20 m below sea level. Over a period of 500 years underground operation, miners have continually excavated more than 700 kilometers of mine roadways, drifts, and blind shafts.

The hydrothermal mercury deposit in Idrija is a geological natural treasure of global significance, and is ranked among the most complex ore deposits in the world. The mercury ore deposit is classified as a monometal, as well as a monomineral, deposit and has the second largest concentration of mercury in the world. Most of the mercury appears in the form of cinnabar (HgS, ~70 %), and in the form of native mercury (Hg, ~30 %). Pyrite, marcasite, dolomite, calcite, kaolinite, epsomite, and idrialin (named after Idrija) represent the main gangue or waste rocks (Mlakar, 1967, 1969; Mlakar and Drovenik, 1971). The mercury ore deposit was formed during two phases: in the lower part of the Middle Triassic (Anisian), and in the second, Ladinian phase during a period of intense volcanic activity in Slovenian geological history. Middle Triassic tectonics led to the upwelling of hydrothermal solutions, which expelled their deposits onto the sea bed through a thick layer of Upper Palaeozoic, Permian, Scythian, and Anisian clastic and carbonate rocks (Mlakar, 1969). Due to gradually declining temperatures, part of the mercury condensed and was released as pure mercury in the form of drops. Hydrothermal underwater springs deposited the mercury in littoral swamps forming the synsedimentary ore beds and lenses in the black Skonca shales and tuffs of the Ladinian age (Mlakar, 1974; Placer, 1976). In the final phase of alpine orogenesis, ore bodies were disintegrated and moved along the faults. The Idrija ore deposit has 158 known orebodies, 17 with native mercury are in carboniferous shale, while the remaining 141 are in clastic and carbonate rocks. These ore bodies have extremely different forms and sizes, and are irregularly distributed throughout the entire ore deposit (Mlakar, 1974; Placer, 1976). The geological cross section is shown in Figure 2.

The ore deposit and its surroundings are comprised of several hydrogeological blocks and impermeable hydrogeological barriers. It is also characterized by the presence of backfills (40 % porosity) and filled shafts on different levels of the ore deposit. The impermeable barriers, enclosing the old part of the Idrija ore deposit, are built of Carboniferous shale below the deposit, thrust sheets along the southern edge, and a Carboniferous layers above the deposit. On the north side, the deposit is closed in by an impermeable, clayey zone of the Idrija fault (Placer and Čar, 1977; Čar, 1990). In all aquifers, the level of ground water is above the level of mine infrastructure. The main inflows of water into the ore deposit occur through shafts, galleries, drilled hydrological barriers or barriers partly demolished due to exploitation works. Due to the geological structure of the Idrija ore deposit, water inflows into the mine facilities are relatively small (average 25 l/s). The flooding of the ore deposit up IXth level (+115 m) keeps mine waters within the limits of the abandoned ore deposit, and the only possible source of pollution with pumped mine water into the above-ground water course – the Idrijca River (+331 m).

3. MINING METHODS USED DURING THE MINE'S OPERATION

In the five centuries of the mine's history the mercury ore mining technologies have employed and adapted to the development of mining science, taking into account existing geomechanics and mining conditions. On the basis of historical sources, the most frequently used the mining method with backfilling from bottom to top, where ore was transported through blind shafts to lower levels and then exported to the surface for further processing. It should be emphasized that throughout the mine's operation, wood was the principal support material used in mining stopes, as well as at the main and auxiliary mine roadways. The cross-stope method which was developed over last 200 years was conducted in several phases, depending on the geometric and geomechanical characteristics of the ore bodies and surrounding rocks. In order to develop an individual level, it was initially necessary to carry out preparations of the main drift on the main level, and install a separate ventilation system so that mining works could be started at individual excavation areas (Fig. 3 A). These were made from a preparatory drift at a 45^0 or 90^0 angle with respect to the main drift axis. The dimensions of the cross-sections in drifts were within the limits of 2.0 m to 4.0 m in width, 1.8 m to 3.0 m in height, and a variety of lengths from a few meters to about 50 m to 80 m in some cases. The horizontal and slightly inclined mine stopes were lined with wood supporting. Ore was transported on various levels and roadways using small and medium-sized mine carts (volume from 0.3 to 0.8 m^3) on wooden and steel rails. After the mine's modernization in the 20th century, mine locomotives were used to transport extracted ore and reproductive materials to various levels, while on working levels the ore was mostly transported manually to blinded shaft or chutes.

Technical evaluation of the mining method from bottom to top is shown in Figure 3 A. The preparation and mining of higher lying levels, was conducted successively after the lower level was backfilled and works had begun on a higher level. The height of each level was approx. 2.5 m to 3.0 m, allowing miners to manually perform all mining works. The relatively complex geological and geotechnical conditions additionally contributed to the worsening mining conditions in higher production levels. In some cases, e.g. when ore was mined from Carboniferous shale, the additional stresses in the rocks on the first level were so intense that mining from bottom to top was practically impossible, because the time-dependent phenomena were so intensive that backfills have still not stabilized. The complex geological and geotechnical conditions accompanying mining works in Carboniferous ore bodies, as well as increased environmental requirements and special concern for the health and safety of miners at work, called for radical changes in the mining method. In the 1970's and 1980's, introduced a new mining method from the top downwards (Bajželj, 1984), which involved highly different mining and backfilling technologies than had previously been used. The new system of mining from the top downwards represented a significant turning point in the history of the mercury mine, as it completely changed individual technological procedures, particularly those designed to protect miners against caving and collapses in the roof and partly also the side walls. The use of reinforced backfill with a minimum required compressive strength, the minimum subsidence was developed and the substantial improvement of mining conditions was achieved.

The final requirement based on a test stopes back analysis, backfill with compressive strength 4 MPa, was sufficient for normal mine operation. This was also proven by calculations used the Finite Element Method, taking into account the nonlinear relations between stresses and strains by means of simulations of mining works and successive use of reinforced backfill into each mining area separately (Bajželj, 1984).

The calculated vertical displacements amounted to maximally 10 cm, which is substantially lower than the subsidence that would have developed when using the old cross-stope method. In addition, mining from the top downwards also has positive effects on the reduction of losses during the mining of mercury ore and native mercury present in Carboniferous shale (Bajželj, 1984).

4. SUMMARY OF MINE CLOSURE WORKS

Several reasons influenced the abandonment of mercury ore excavation, initially in the 1970's and finally in the late 1980's. On the one side, an intensive international campaign had been launched against mercury, whose harmful effects were researched in various fields. Another reason was the very low selling price of this metal, which in some cases fell below 100 USD per flask (34.5 kg of mercury). All activities which were done in preparing mine closure works faced particular issues on the long-term effects on the time dependent surface subsidence (Cigale, 1988). More questions were raised, because the town of Idrija location is directly above the mining infrastructure. In addition, the potential instability of the natural and artificial slopes above the mine, and the pollution of the environment with mercury in the town of Idrija itself and far downstream along the Idrijca River and the Soča River, including the Gulf of Trieste, were present as well (Režun and Dizdarevič, 1997). The principal tasks were to select and justify the technology required for mine closure works, with the clear goal of attaining the long-term stability of the vibrant surface area above the mine, reducing to the greatest possible extent any possible damage to buildings caused by mining activities, regulating the hydrological and hydrogeological environments, establishing supervision over harmful concentrations of mercury in various forms or aggregate states, and constantly controlling the effects of mercury on miners and other inhabitants of the town of Idrija. Surveying and geometric observations of surface movements in the wider area of the mine from the beginning of the 20th century onwards, as well as the excellent geological and hydrogeological studies and interpretations of the origin of the ore deposit and subsequent tectonic and other occurrences are a useable base for deep interpretation for the complex deformation process. For this purpose, extensive simulations and analyses of the impact of reinforcement processes on the rock structure and old mining works using the finite element method were performed (Bajželj and Likar, 1991). A specific question was raised in connection with the estimated consequences of possible flooding of the mine up to different height levels, as the considerable worsening of geotechnical conditions was expected in areas where mine water came into contact with rocks and old backfills, which are sensitive to water. In situ investigations in the mine confirmed the fear that increased surface subsidence would develop in the event of uncontrolled flooding of the mine. This is the main reason for anticipated flooding level was deeper instead of the first assumptions. In this context intensive grouting of old mine works and backfills including mine roadways, drifts and vertical mine connections were done over more than 10 years.

5. MEASUREMENTS OF GEOTECHNICAL AND HYDROGEOLOGICAL PARAMETERS

Geodetic measurements began in the initial years of the 20th century, while extensive geometric observations aimed at monitoring the stabilization of the mine were not performed until year 1990. Measurement was carried out in profiles net installed on the disturbed surface above the mine. Measurements were also performed on important infrastructural buildings and facilities, too. Before the commencement of shutdown works, the horizontal and vertical movements of terrain above the mine were up to 25 mm/year and up to 14 mm/year, respectively (Likar et al., 2006).

5.1. DISPLACEMENTS MEASUREMENTS IN THE MINE

The wide mine surveying mesh included measuring points placed on different mine levels connected to main points near the main shafts "Joseph" and "Francis" (Fig. 1). Each measuring point is stabilized on the bottom or in the roof of mine roadways to allow for the measurement of vertical movements and, in some cases, horizontal movements as well. Each measuring cycle was performed twice per year with the aim to keep subsidence control. A trend of vertical displacement similar to that on the surface was also found in the mine. The measurements executed on levels I to XI showed a displacement syncline near the Inzaghi shaft (Fig. 2), where a maximum subsidence was found. The measured movements gradually decreased and, during the past years, horizontal movements declined to an average 8 mm/year and vertical displacements to 4 mm/year. The typical result of vertical movements is shown in Figure 4.

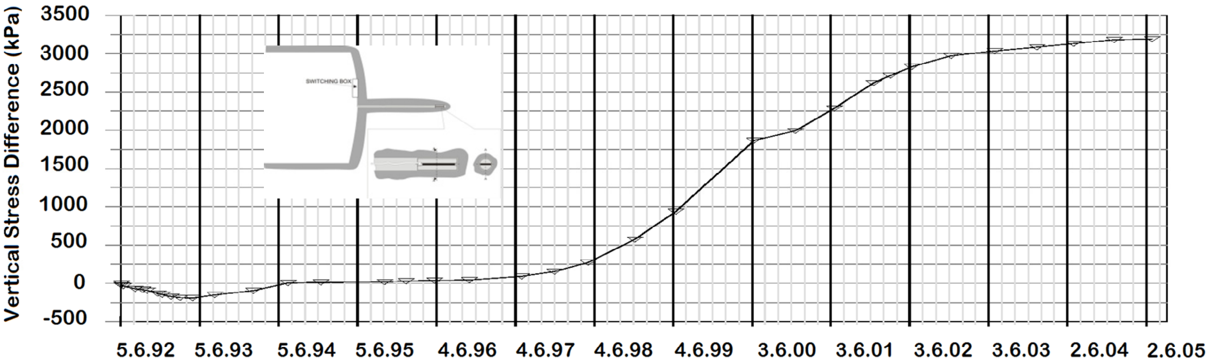

Fig. 6 Results of the additional vertical stress measurement in the shale on the XVth level.

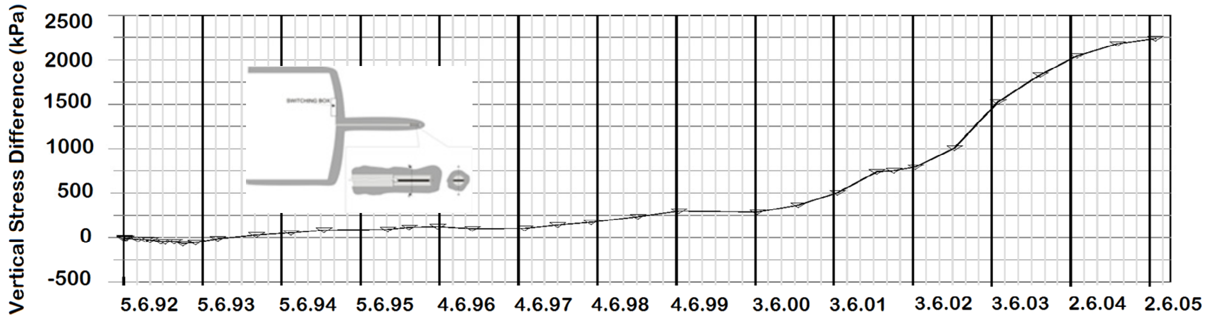

Fig. 7 Results of the additional vertical stress measurement in the dolomite on the XIVth level.

5.2. HORIZONTAL DISPLACEMENT MEASURED BY INCLINOMETERS

Inclinometer measurements in boreholes have been conducted since 1989. In the period from 1989 to 1996, 17 inclionometric boreholes were activated and measurement carried out twice a year, and attained values of up to 21 mm/year and vertical movements of up to 10 mm/year (Fig. 5.). The period from 1996 to 2001 has shown that the terrain above the mine continues to move, but with a decreasing tendency as a result of consolidation and fortifying works. In the last eight years (2003 – 2011), we measured some local increasing deformations in an area with geotechnical, unstable rocks (Carboniferous shale), but these are still in the process of stabilizing and do not present any major hazard.

The results of several years of measurements and observations have shown that not only are different slow slides forming above the mine, but a large subsiding crater is also forming with its center around the Inzaghi shaft (Fig. 2.), where most of the exploitation works took place over the last 100 years.

5.3. MEASUREMENTS STRESS CHANGES IN ROCKS AND BACKFILLS

A very important part of measured data was related to determining secondary stress changes with time in different locations at the deepest levels in the mine. For the purpose of monitoring stress deformation changes in rocks and backfills in the deepest parts of the mine during flooding up to the XIth level, measurement probes, i.e. cells equipped with a strain gauge in the vertical direction tested in the laboratory in biaxial cell, were incorporated into boreholes, and injected with cement grouting material. Since the incorporation of measurement probes at the XIVth and XVth levels in the middle of 1992, measurements of specific deformations in backfill (XIVth level, elevation – 6.45), dolomite (XIVth level, elevation. – 6.45), and shale (XVth level, elevation – 32) have been performed twice yearly.

The results of these measurements are shown in Figure 6 and Figure 7 at the XIVth and XVth levels where the deformation processes were in progress during the time when the flooding of lower part of the mine was present.

It is evident from the results of measurements shown in Figure 6 in the form of diagram that the course of time-dependent stress changed in 1995 and partly in 1996, when changes in stresses and deformations in the rock structure occurred as the consequence of mine flooding up to the XIth level. Rapid changes in deformations stopped occurring later on. The results of measurements indicated that the deformation processes are still in progress, but the trends do not point to any major stress changes in surrounding rocks. All measuring points still indicate changes in increasing vertical stresses particularly in shale.

It is highly probably that the changes found are linked to the sinking of areas above mine extraction works, and the effects of time-dependant occurrences around the Idrija fault where stress changes have been more intensive in dolomite on the XIVth level, while those in shale on the XVth level are rapidly decreasing.

Measurements of secondary stress states on the IVth, VI^{th,} and VIIth levels with triaxial cells for the measurement of stress changes were installed on the IVth level in the beginning of 1996, on the VIIth level in December 1996, and on the VIth level in July 2004. In the most recent period, measurements were performed twice a year in order to determine whether there are any stress changes in consolidated backfills in the broader area, where extensive mining works were performed in the past. The results of measurements shown in Figure 8 indicate that the time-dependent secondary stresses changes considerably more extensive with no continue trends because consolidated backfills persisted in time intervals. The substantially increased stress on cells on the IVth level is explained by the fact that the rigidity of old reinforced backfills in the broader areas is incomparably higher than in other backfills, which were not additionally injected or grouted. Results on the VIIth level have shown strain softening deformation process because the lower backfill layers and low bearing ground strata weren't grouted enough (Likar et al., 2006).

6. EVALUATION OF ADEQUACY EXECUTED CONSOLIDATED WORKS

It cannot be denied that five centuries of the mine's operation below the town of Idrija have caused various changes in the mine, the rock structure in the vicinity of the mine, and on the surface. Although mining works were continuously accompanied by backfilling of dug out areas during the mine's entire operation, the backfills were so deformable that they were unable to prevent surface subsidence. Also, their rheological characteristics were not such as to reduce subsidence without additional reinforcement measures. Frequent visual inspections of various facilities on the surface have shown that the intensity of time-dependent displacement is gradually decreasing, and that damage in the form of cracks and shear movements has also decreased considerably. In some cases cracks were more open in a specific period, but closed after a number of years. It may therefore be concluded that the time dependent movements of the surface was not uniform, and that reinforcement measures indirectly influenced the gradual reduction of damage on the surface. Grouted and backfilling works can be evaluated based on results of presented measurements and observations which indicate that adequacy of planned and executed procedures are in the expected domain. Retaining walls and other surface civil structures only cracked and damaged to the extent of requiring rehabilitation when the time gradient of deformations will be sufficiently small, or when a differential subsidence rate will be less than 1cm/year. Similar requests can be used in the case of building new structures and rehabilitation works on existing civil facilities. The estimation of time-dependent deformations on the surface above the mine has allowed us to prepare a prognosis of the development of the deformation field in the next 10 or 20 years. According to the simple linear approximation shown in Figure 9, the time dependent subsidence can be expected to continue for at least 10 years.

7. CONCLUSIONS

More than five centuries of mining activity in the area below the town of Idrija have caused major changes in the stress strain states of rocks and backfills in the affected areas of the mercury mine. Some implementations of measures for improvement of the rock structure and backfills were done in the period of intensive mercury ore extraction.

The present complex geological structure in the wider area of the Idrija Mercury Mine, including major tectonic and neo-tectonics occurrences with extreme geological changes are the principal factors which, alongside mining works, continue to influence the development of deformation fields in the mine and on the hilly surface.

In past, before the mine closure works had approved, extensive numerical models were done by checked, proposed, grouted, and other consolidation measures supported by laboratory and in situ investigations in the goal to determine the geotechnical characteristics of rock mass and backfills.

Different measurements and observations were carried out in the mine and on the surface, with particularly attention on making an analysis of time dependent movements of unstable surface areas. These included inclinometric and piezometric measurements, as well as measurements of stress changes using measuring cells, which are still used today and will continue after the completion of the shutdown works.

Time-dependent occurrences of potential sliding areas on the surface and in mine rocks and subsidence of artificial backfills are still present, but the intensity of time-dependant movements is considerably reduced.

Analysis and calculation of the development time-dependent surface subsidence shows that in the coming years certain areas can be used to build facilities that will be tolerated by smaller differential settlements around 0.25 %.

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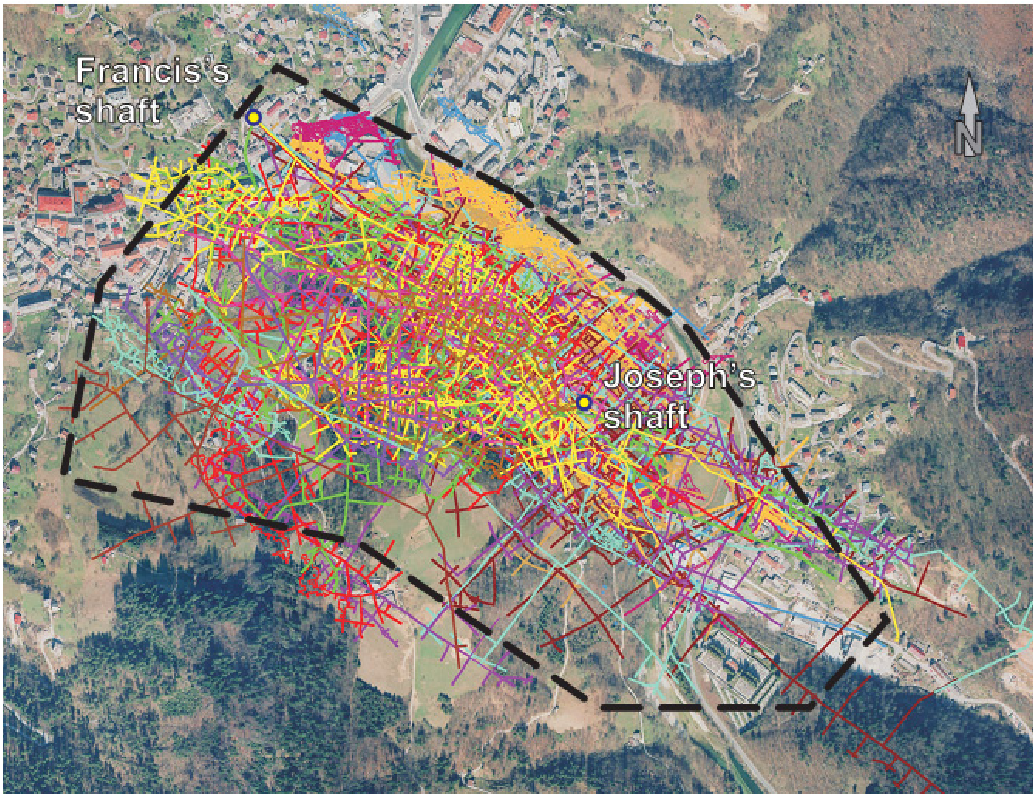


Fig. 1 Layout of the town Idrija with Mercury Mine Structure.

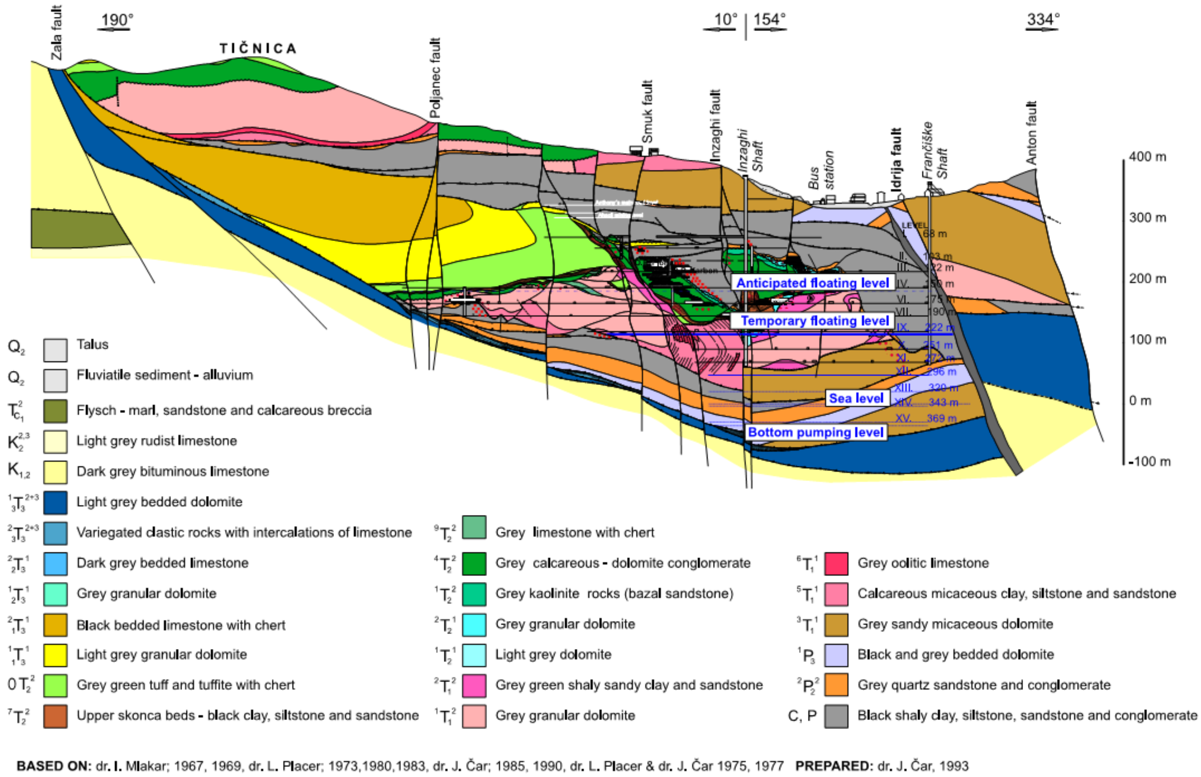


Fig. 2 Geological cross section through the Idrija Mercury Mine (Čar, 1993).

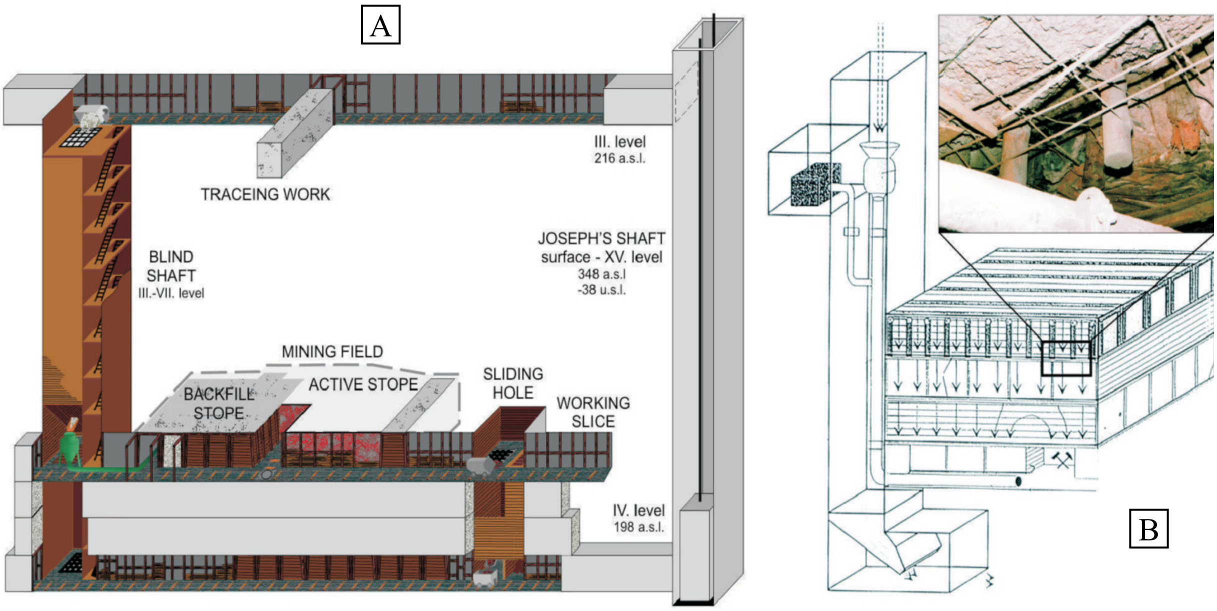


Fig. 3 Cross stopping with backfill and sublevel mining with consolidated backfilling.

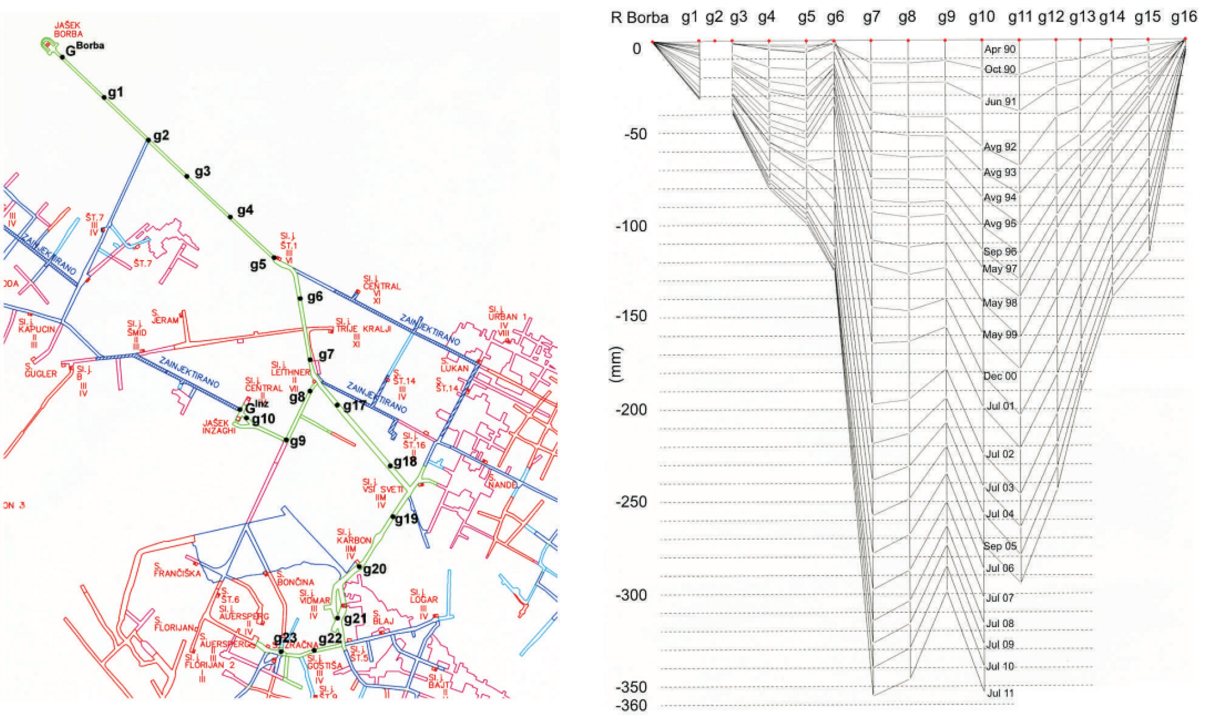


Fig. 4 Measured settlements at the IIIth level.

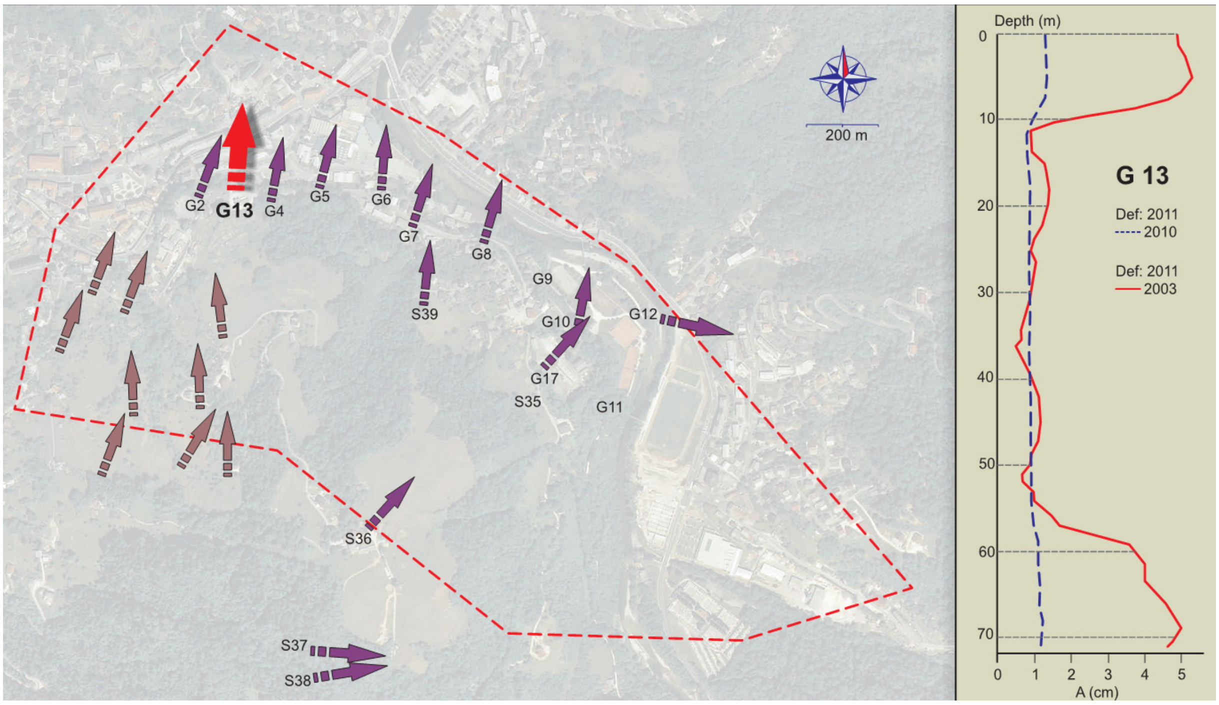
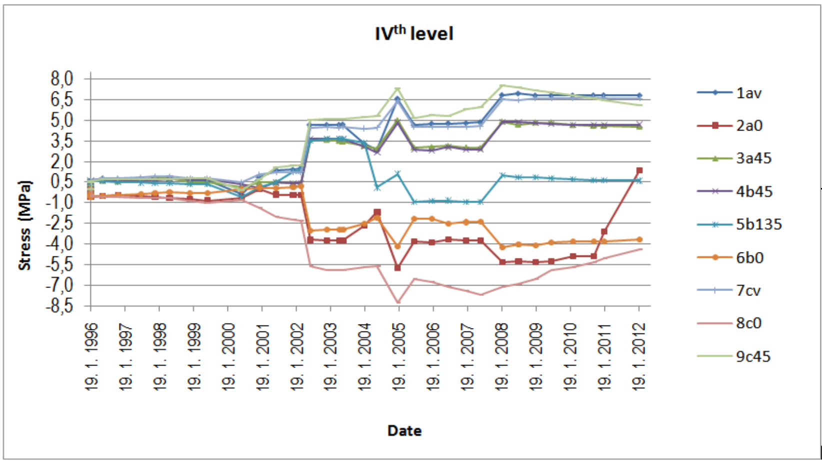
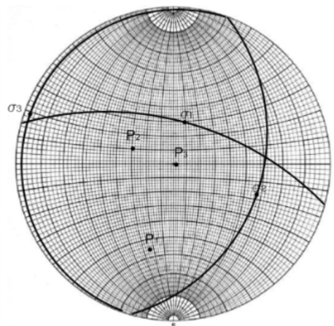


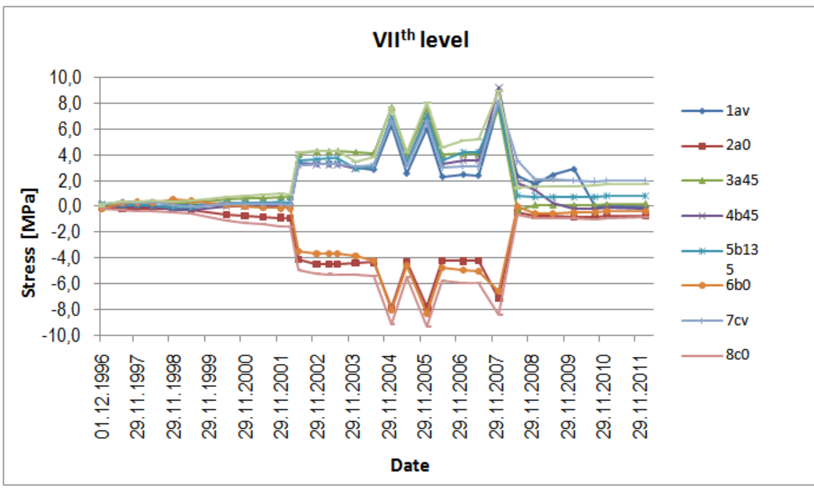
Fig. 5 Results of the inclinometer measurement G13.



Average Values till January 06

Main stress	σ_1	σ_2	σ_3
Dip (^{0})	61.77	28.22	0.71
Azimuth (^{0})	65.58	153.89	334.27
Value of stress (MPa)	5.06	0.39	-1.42





Main stress	σ_1	σ_2	σ_3
Dip (^{0})	59.14	30.77	2.12
Azimuth (^{0})	15.42	110.23	288.97
Value of stress (MPa)	7.84	-0.12	-2.18

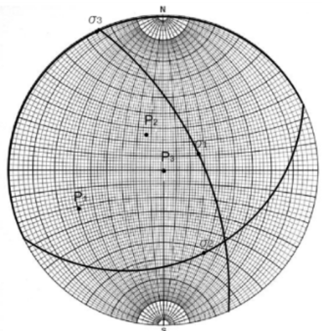


Fig. 8 Stress changes versus time in the consolidated backfill on the IVth level and VIIth level with triaxial cells.

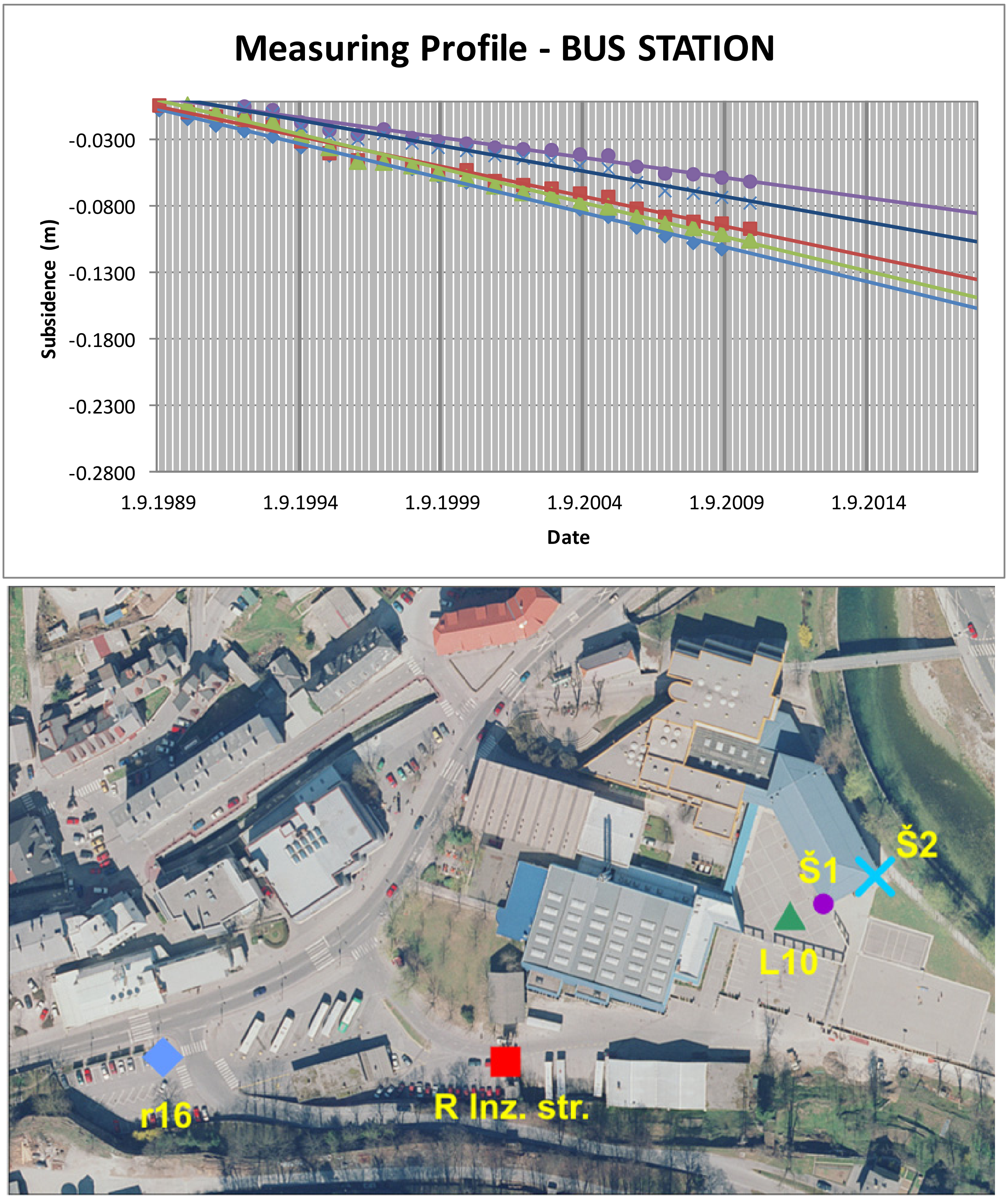


Fig. 9 Estimation of the time dependent settlements of points in measuring profile BUS STATION on the surface above the mine (see Fig. 2.).