

Long-term deformation processes in the wider area of the closed Idrija Mercury Mine

Dolgotrajni deformacijski proces v širšem območju Rudnika živega srebra Idrija

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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. In order to guarantee safe and technically progressive ore mining, permanent pumping of mine water and the constant modernization of technology and other working fields, including ore processing and heating, increased ore production, the spread of mine works into greater depths, and difficult rock conditions have in the past demanded the effective cooperation of different branches of technical and natural sciences. During the many years of mercury ore excavation, the cross-stope mining method with backfilling from down to up in low-bearing rocks was used. Mine shutdown works, which include grouting and hardening destroyed areas, as well as filling parts of the mine and backfilling empty spaces (i.e. mine roadways), are now in the final stage. The efficiency of mine shutdown works is constantly being verified by means of geotechnical and other measurements and observations, while considering the local rock conditions. The paper presents some results of the measurements and observations performed, as well as the changes in the wider area of the Idrija Mercury Mine during shutdown works and an estimation of surface deformation changes in future.

Povzetek: Dolga doba obratovanja Rudnika živega srebra v Idriji (SLO) v preteklih petih stoletjih je za sabo pustila posledice, ki se kažejo na okolju in posredno še vedno vplivajo na deformacijska dogajanja na širšem raziskovalnem območju. Postopno večanje proizvodnje rude, širjenje rudarskih del v večje globine in zahtevne hribinske razmere odkopavanja, so v preteklosti zahtevali učinkovito sodelovanje različnih strok. Dolgotrajno odkopavanje živosrebrne rude, ki je potekalo z uporabo t.i. prečne odkopne metode za zasipavanjem odkopnih prostorov od spodaj navzgor v relativno zahtevnih hribinskih pogojih. Zapiralna dela, ki vključujejo tudi injektiranje in utrjevanje porušeni območij ter starih zasipov, kakor tudi zasipavanje praznih prostorov, so v zaključni fazi. Uspešnost teh del se stalno preverja z geotehničnimi meritvami in drugimi opazovanji, ob upoštevanju lokalnih hribinskih pogojev. Nekateri rezultati teh opazovanj in meritev so podani v prispevku v okviru interpretacij dogajanj na območju Rudnika živega srebra med zapiralnimi deli z oceno možnih deformacijskih sprememb v prihodnosti.

Key words: Mercury mine, rock structure, sublevel mining method, reinforced backfill, stress measurement in rocks, surface displacement, analyses of the time dependant processes; old fill grouting

Ključne besede: Rudnik živega srebra, struktura kamnin, podetžna odkopna metoda, meritve napetosti v kamninah, pomiki površine, analize časovno odvisnih procesov; utrjevanje starih zasipov

INTRODUCTON

Sinking terrain and other deformations are an integral part of the occurrences in the wider area of the closed Idrija Mercury Mine. The mine closure works are progressing in accordance with the approved program, which includes various observations and measurements in the mine and on the surface above the mine. To ensure the stabilization of broader rock areas over the long term, the filling and injection of areas with the highest deformation intensity is of great significance.

The time-dependant deformation processes currently in progress in the wider area of the Idrija Mercury Mine were monitored by surveying and other measurements and geological-geotechnical observations. The measurements were conducted in the prescribed time intervals twice a year in order to ensure the time-dependant 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 reinforcement works and other activities in the mine and on the surface. Although mining works were stopped more than ten years ago, the sinking and subsidence of time-dependant areas in the pit and on the surface have not yet stabilized completely. Long-term time-dependant processes, which are closely linked to the methods and extent of ore mining in the past, and in particular to the natural geological conditions, primary stress states and other influences, are still present particularly in areas built of Permian-Carboniferous layers and other low-bearing-capacity rocks. The sublevel mining method with reinforced backfilling from the top downwards^[1], introduced in the last years of the mine's operation, had a significant impact on the reduced intensity of deformation processes in the mine, and consequently on the surface above the mining fields.

The final stabilization of the area therefore depends on a gradually stabilized deformation field, which will indirectly have a favorable impact on eventual construction projects in the area concerned.



Figure 1. Layout of the town Idrija with Mercury Mine
Slika 1. Lokacija mesta Idrija z Rudnikom živega srebra

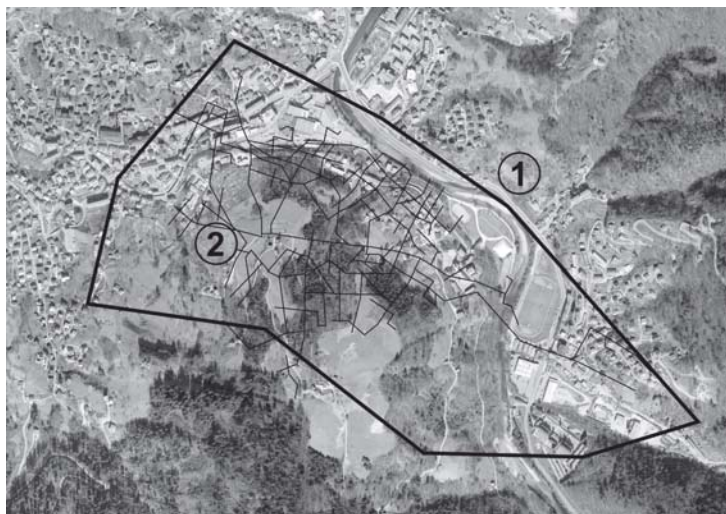


Figure 2. Layout of the Idrija Mercury Mine
Slika 2. Območje Rudnika živega srebra Idrija

GEOLOGICAL AND HYDROGEOLOGICAL INTERPRETATION OF THE WIDER MERCURY MINE AREA

The Idrija mercury ore deposit is located directly below the town of Idrija between the Idrijca River and its tributary, the Nikova stream. The ore deposit extends in the directions north-west and south-east. It is 1500 m long and 300-600 m wide. The depth of the ore-bearing zone is about 450 m. The deposit is open and has vertical shafts. The deepest shaft reached a depth of 420 m and linked all 15 levels, the lowest of which extended 36 m below sea level. The distance between levels varies from 15 to 30 m. Over a period of five hundred years, miners have dug out more than 700 kilometers of roadways and shafts. Today, only about 20 km of roadways are still open.

Geology

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 Idrija ore deposit is classified as a monometal as well as a monomineral deposit. It has the second largest concentration of mercury in the world, second only to Almaden in Spain. Most of the mercury appears in the form of cinnabar (HgS , ~70%), and the remainder 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.

The Idrija ore deposit was formed during two phases: in the lower part of 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

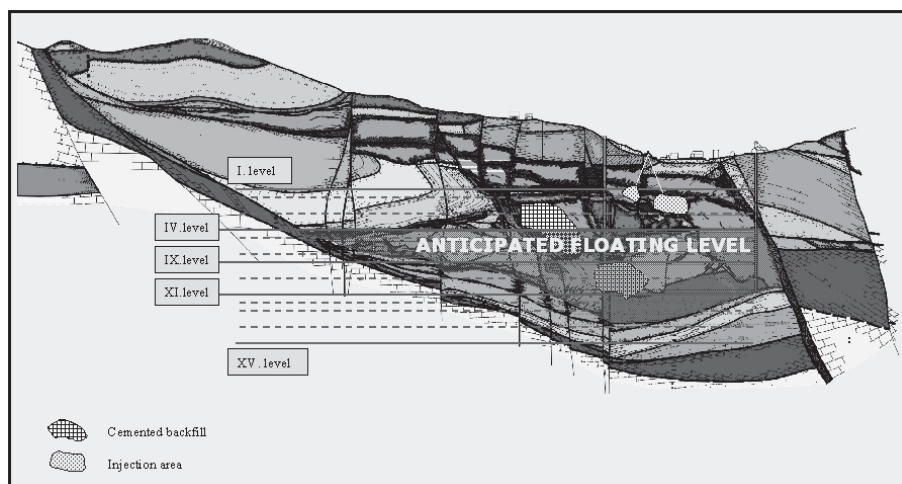


Figure 3. Geological cross section through the Idrija Mercury Mine

Slika 3. Geološki prerez Rudnika živega srebra Idrija

Anisian clastic and carbonate rocks. 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 syndimentary ore beds and lenses in the black Skonca shales and tuffs of the Ladinian age.

The geological structure of the Idrija ore deposit is fairly complicated as the result of tectonic activity. The ore deposit was cut into blocks by napping and thrusting. 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.

Hydrogeology of the ore deposit

The ore deposit and its surroundings are comprised of several hydrogeological blocks and impermeable hydrogeological barriers. The hydrogeological block of the Idrija ore deposit is highly specific. It is also characterized by the presence of backfills (40 % porosity) and unfilled shafts on lower 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 layer above the deposit. On the north side, the deposit is closed in by an impermeable, clayey zone of the Idrija fault. In all aquifers, the level of ground water is above the level of mine infrastructure. The pit waters do not supply water to any of the aquifers in the vicinity, but precisely the opposite – the waters of neighboring aquifers flow into the pit. The main inflows of water

into the ore deposit occur through shafts, galleries, drilled hydrological barriers or barriers partly demolished due to excavation works.

The flooding of the ore deposit up to the IVth level (+192 m) will keep pit waters within the limits of the abandoned ore deposit, and the only possible source of pollution with pumped pit water will be at the discharge into the above-ground water course – the Idrijca River (+331 m). At present, the pit is flooded up to the IXth level (+115 m)

Due to the geological structure of the Idrija ore deposit, water inflows into the pit facilities are relatively small (average 25 l/s). Approximately half of the water comes from the carbonate cover above the ore deposit, while the remainder comes from indirect sources in the periphery of the pit structure.

MERCURY ORE MINING METHODS USED DURING THE MINE'S OPERATION

The mercury ore mining technologies employed in the five centuries of the mine's history were adapted to the state of development of mining science and the existing natural mining conditions. On the basis of historical sources, we have assessed that the most frequently used was the mining method with backfilling from down to up, where ore was released through jack pits 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 material used to make supports in mining areas, as well as at the main and auxiliary gates on

various levels. These gates were developed between levels in the areas of individual ore bodies.

Particularities of the cross-stope mining method

Ore mining using the cross-stope mining method required a good knowledge of the behavior of strata in relatively tectonic and mechanically damaged rocks embodied in the hanging wall, mineralized and footwall layers of the ore deposit. It should be noted that the inflows of underground water were relatively low in view of the size of open ore bodies, which on the one side had a favorable effect on the development of mining works. Strata water frequently appeared in the lower levels of the mine and, in exceptional cases, on higher levels, e.g. the IVth level of the mine.

Ore extraction using the above-mentioned method was conducted in several phases, depending on the geometric and geotechnical characteristics of the ore body and surrounding layers. In order to develop an individual level, it was initially necessary to carry out preparations of the main gate on the main level and install a separate ventilation system so that mining works could be started at individual excavation areas. These were made from a preparatory gate at a 45° or 90° angle with respect to the main axis. The dimensions of the cross-sections in the preparatory gate and in individual excavation areas 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 ranging from a few meters to about 50 m to 80 m in some cases. The horizontal and

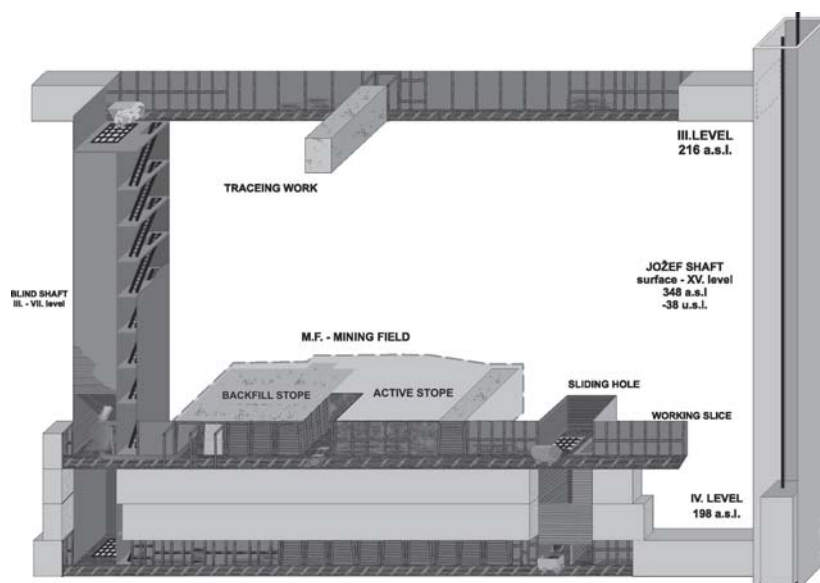


Figure 4. Cross stopping with backfill

Slika 4. Odkopavanje rude s prečno odkopno metodo z zasipom

slightly inclined mine areas were lined with wood supporting. Wood support was also installed in back mines, jack pits and chutes connecting individual levels and intermediate levels where ore was mined.

Ore was transported on various levels and roadways used small and medium-sized mine carts (volume from 0.3 to 0.8 m³) 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.

Geotechnical evaluation of mining method from down to up

Changes in primary stress-strain states as the consequence of ore extraction works

occurred in surrounding rocks and ore bodies, and gradually increased with the increasing volume of extracted ore and gangue in areas where the existing natural conditions called for the excavation of individual masses of no mineralized rock. Although excavation areas were backfilled regularly, the filling material was quite compressible and deformable, resulting in minor stress-strain concentrations in backfilled spaces and indirectly in increased deformations, which were transferred to the wood supporting and particularly to the surrounding rocks.

The preparation and mining of higher lying levels, as shown in Figure 4, was conducted successively after the lower level was backfilled and works were begun on a higher level. The height of each level was approx. 2.5 m to 3.0 m, allowing miners to manually perform such works as drilling, blasting,

loading and transporting of extracted ore, as well as installing wood supporting and, finally, backfilling excavated mining areas. The relatively complex geological-geotechnical conditions, part of which is presented in the geological description of the ore deposit, additionally contributed to the worsening mining conditions in higher-lying levels. In practice, this was evident in the increasingly more damaged rock masses and additional stresses on the wood supporting which, considering its subsidence and collapsibility, survived the increased pressure of the rock mass relatively well. In some cases, e.g. when ore was extracted from Carboniferous shale, the additional stresses in the rocks on the first level were so intense that mining from down to up was practically impossible.

In addition to the above-mentioned, the time-dependant phenomena were so intensive that reprofiling had to be performed already during ore extraction on the first level. The above-described occurrences of gradually sliding rocks and backfills have not stabilized to this day.

Mining method with consolidated back filling from the top downwards

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 ore extraction method. In the 1970's and

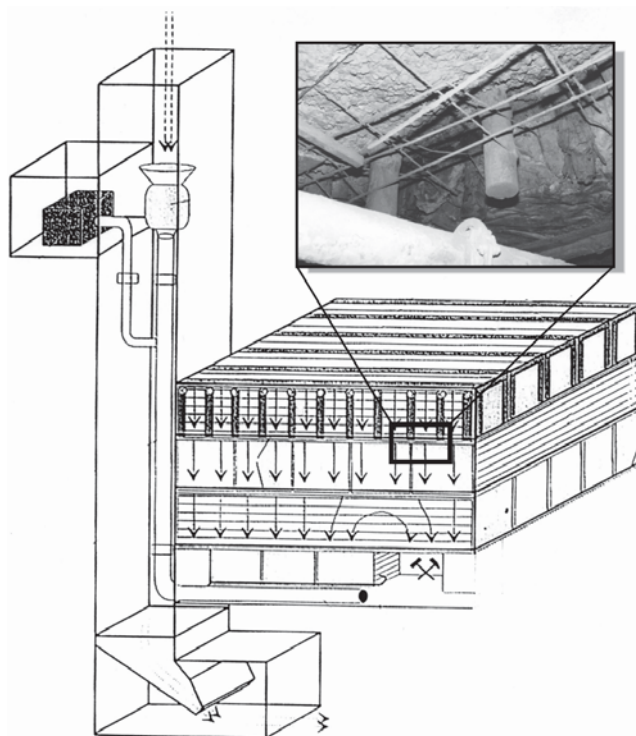


Figure 5. Principles of the sublevel mining with consolidated backfilling
Slika 5. Principi podetažnega odkopavanja rude z utrjenim zasipom

1980's, Prof. U. BAJŽELJ^[1] introduced a new mining method from the top downwards, which involved highly different mining and backfilling technologies than had previously been used.

Particularities of mining from the top downwards

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 of the ceiling and partly also the side walls. The use of reinforced backfill with a minimum required strength and minimum subsidence contributed to the substantial improvement of mining conditions. Figure 5 shows the mining method from the top downwards using reinforced backfill with a compressive strength of 6.5 MPa, which was still sufficient to ensure the prescribed stability conditions during mining works in lower levels. The final requirement for normal mine operation, backfill with compressive strength 4 MPa was sufficient.

Since the established mining method had not changed significantly for more than a century, the introductory procedures were carefully planned and gradually implemented in the so-called trial mining area in Carboniferous shale on the IVth level (Figure 5) at a depth of 150 m.

An analysis of the results of trial mining works showed encouraging results and the possibility of introducing the proposed sublevel mining method with reinforced backfilling also in the excavation of other ore bodies.

Geotechnical evaluation of mining from the top downwards

From the geotechnical aspect, the transfer of secondary stress deformation states to surrounding rock strata and consolidated backfilling also represents a considerable reduction of shifts occurring with this mining method. The small deformability of backfilling material and the minimal compressive strength compensate for the additional stresses in the backfill itself. It should be emphasized that the strength characteristics of surrounding rocks – particularly Carboniferous shale – are lower than those of the consolidated backfill, which means that technical conditions of mining works improve with the increasing size of mining areas, and indirectly with the changed material of higher strength. 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 injections of reinforced backfill into each mining area separately^[2].

The calculated deformations amounted to maximally 10 cm, which is substantially lower than the deformations that would have developed in the old mining method from down to up, i.e. the so-called cross-stope method.

In addition to the above-mentioned, 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.

DETERMINATION OF SHUTDOWN WORKS AND THEIR EXECUTION

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 USD 100 per flask (34.5 kg of mercury). Several years passed before the state administration adopted a decision on the gradual shutdown of the mine and the long-term abandonment of mercury production. In addition to the above-mentioned factors, particular emphasis was laid on the long-term effects of the mine on the sinking surface, i.e. the town of Idrija, which stands directly above the mining facilities, 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.

The principal tasks were to select and justify the technology required for shutdown 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 and the broader affected region.

Estimation of geological and geotechnical conditions prior to determining the mine shutdown procedure

Surveying and geometric observations of surface shifts in the broader affected 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, have enabled engineers to evaluate various parameters serving as a basis for the formation of a strategy of gradual shutdown of the mine and mining facilities, including the rehabilitation of ore residue deposits. On the basis of a well argument analysis of planned shutdown works, the legislative body of the government passed a law ensuring the allocation of funds for the execution of planned works, accompanied by regular controls and measurements of the effects of such works on set goals. 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. A specific question was raised in connection with the estimated consequences of possible flooding of the pit up to different height levels, as the considerable worsening of geotechnical conditions was expected in areas where pit 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 shifts would develop in the event of uncontrolled flooding of the mine. For this reason, a plan foreseeing the gradual reinforcement and backfilling of empty spaces as well as flooding of the mine in several phases was adopted. These

procedures would be accompanied by regular controls of deformation changes in the mine and on the surface in the broader affected area of the mine. The proposed measures were approved by the state authorities, which passed a relevant law and allocated funds for financing shutdown works and research activities.

Methods of execution of shutdown works

The gradual shutdown of the mine and the rehabilitation of the area of the mine's operation on the surface is progressing according to project solutions and the adopted shutdown strategy, and in line with the long-term rehabilitation of degraded areas. Special attention has been devoted in past years to the improvement of reinforcement and backfilling technologies, as most of the vertical and horizontal mine areas below the IVth level have been filled with reinforced backfill. For the purpose of injection and backfilling of pit areas, a special injection device was erected on the surface above the mine. The device is used to pump backfilling materials into lower lying mine areas through an open shaft and drill holes.

The pumping capacity is around 10,000 m³ per year, which in view of the selected technology is the optimal capacity. Problems have arisen due to our unfamiliarity with the exact position and size of abandoned underground areas, which has rendered the planning of quantities and volume of required backfilling materials difficult.

The shutdown works in those sections of the pit where backfilling was not necessary due to the solid rock structure generally comprised the removal of steel, wooden and

other parts in order to reduce their potential effects on mine water.

In my estimate, the shutdown works will be completed by the year 2010.

MEASUREMENTS OF GEOTECHNICAL AND HYDROGEOLOGICAL PARAMETERS

Geodetic measurements on the surface

Geodetic measurements were begun in the initial years of the 20th century, while extensive geometric observations aimed at monitoring the stabilization of the mine were not performed until 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.

Displacement 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 "Delo" and "Borba". 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 if any extreme displacements occurred as the result of closure works or during flooding of the deeper part of the mine.

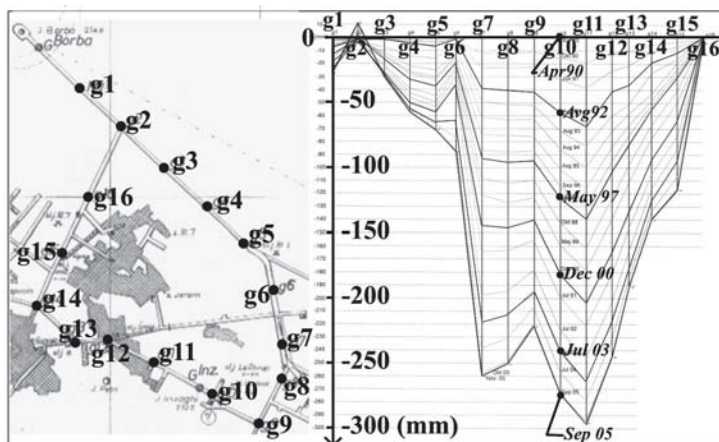


Figure 6. Measured settlements at the IIIrd level

Slika 6. Izmerjeni posedki na III. obzorju

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, where a maximum subsidence was found. The measured movements gradually decreased and, in the past year, horizontal movements declined to an average 8 mm and vertical displacements to 4 mm. The typical result of vertical movements is shown in Figure 6.

Measurements of horizontal displacement in vertical inclinometers

Measurements of inclinometric boreholes have been conducted since 1989. The boreholes are located in areas with the most intensive shifts. In the period from 1989 to 1996, 17 inclinometric boreholes were activated. In that year the horizontal shifts, measured twice a year, attained values of up to 21 mm/year and vertical shifts of up to



Figure 7. Results of the inclinometer measurement G9

Slika 7. Rezultati inklinometriških meritev merskega mesta G9

10 mm/year. However, measurements of inclinometric borehole deformations conducted in the period from 1996 to 2001 have shown that the shifting of terrain above the pit is continuing, but with a decreasing tendency, which is undoubtedly the consequence of the abandonment of excavation works and the conduction of consolidation-fortifying works in the pit. In the last four years (2001 – 2005), 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 slides forming above the pit, but a large sinking crater is also forming with its centre around the Inzaghi shaft, where most of the excavation works took place.

Measurements of stress changes using measurement cells

In addition to other measurements and observations, probes were initially incorporated at various locations to monitor stress deformation changes in rocks and backfills during shutdown works and partial flooding of the mine. The measurements described below have served to illuminate the deformation processes in progress. Our principal intention, however, was to determine the impacts of flooding of part of the pit on the rock structure of the mine.

Measurements of secondary stress deformation changes at the XIVth and XVth levels

For the purpose of monitoring stress deformation changes in rocks and backfills in the deepest parts of the pit during flooding up to the XIth level, measurement probes, i.e. cells equipped with “strain gauges” in different directions, were incorporated into boreholes and injected with cement grouting material.

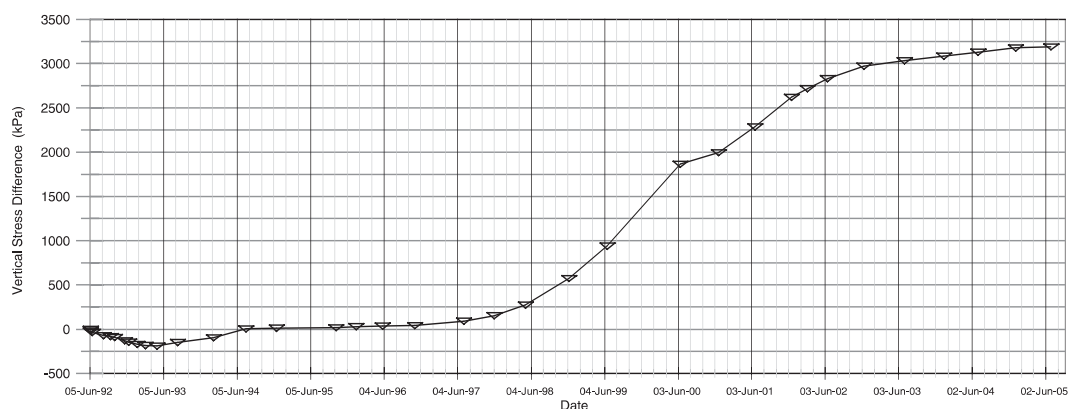


Figure 8. Results of the additional vertical stress measurement in the shale on the XVth level
Slika 8. Rezultati meritev dodatnih vertikalnih napetosti v skrilavcu na XV. obzorju

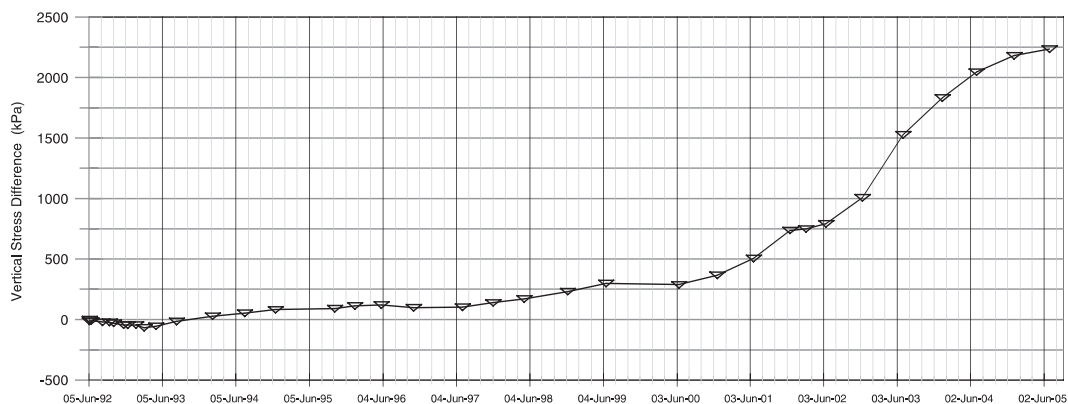


Figure 9. Results of the additional vertical stress measurement in the dolomite on the XIVth level

Slika 9. Rezultati meritev dodatnih vertikalnih napetosti v dolomitu na XIV. obzorju

Since the incorporation of measurement probes at the XIVth and XVth levels in the middle of 1992, i.e. in the past 13 years, 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.

It is evident from the results of measurements shown in Figure 8 in the form of diagram that the course of time-dependant deformations changed in 1995 and partly in 1996, when shifts or 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 in the past year indicate 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. This is more pronounced in dolomite and, to a smaller

extent, in shale, which may be explained by the greater rigidity of dolomite.

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. In the past four years, stress changes (shifts) 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, VIth and VIIth levels

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 have been 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 10 indicate that the time-dependant changes occurring in the past year are considerably more extensive than in approximately the same time intervals in previous years. The substantially increased stress in cells on the

IVth and VIIth levels 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.

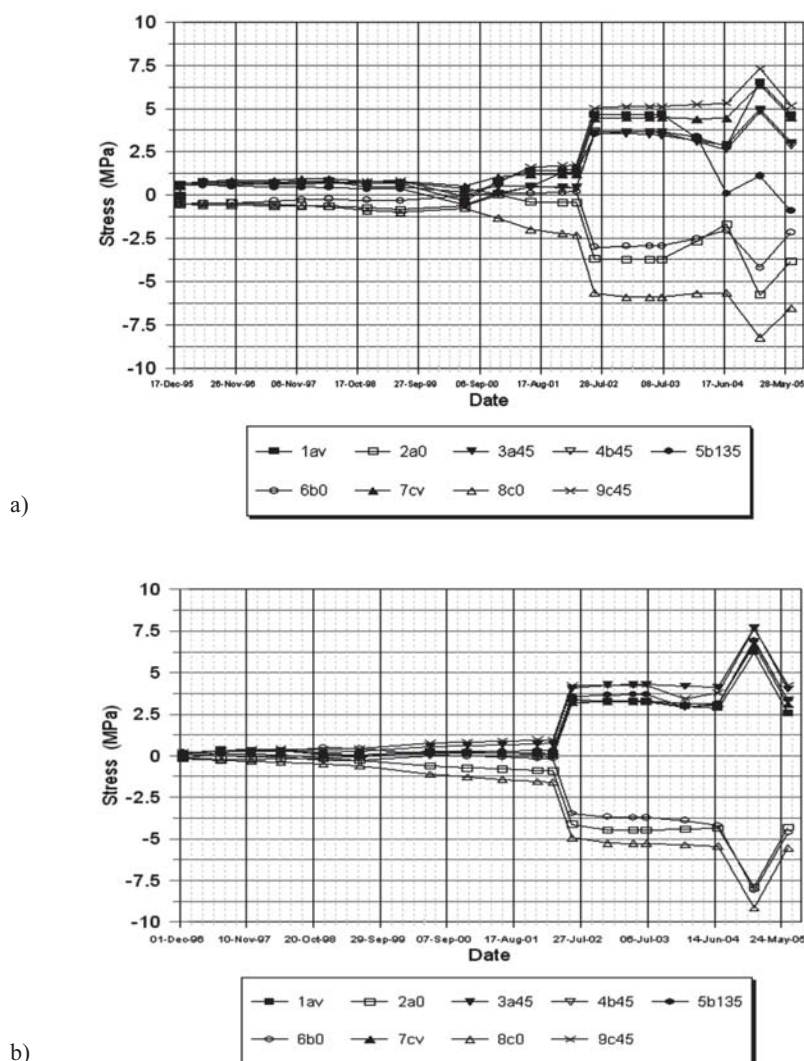


Figure 10. Stress changes versus time in the consolidated backfill on the
a) IVth level **b)** VIIth level measured by triaxial cell

Slika 10. Časovno odvisne spremembe napetostnih stanj v utrjenem zasipu izmerjene s triosnimi celicami **a)** na IV. obzorju, **b)** na VII. obzorju

EVALUATION OF ADEQUACY OF EXECUTED CONSOLIDATED WORKS

Although the success of reinforcement and backfilling works cannot be evaluated at present, a number of indicators point to the adequacy of planned and executed procedures. It cannot be denied that five centuries of the mine's operation below the town of Idrija have caused various changes in the mine, 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 the sinking of the surface, and their rheological characteristics were not such as to reduce sinking without additional reinforcement measures.

Visual assessment of adequacy of shutdown works

Frequent visual inspections of various facilities on the surface have shown that the intensity of time-dependant shifts is gradually decreasing, and that damage in the form of cracks and shear shifts has also decreased considerably. In some cases when cracks were more open in a specific period, but closed after a number of years. It may therefore be concluded that the sinking of the surface was not uniform and that reinforcement measures indirectly influenced the gradual reduction of damage on the surface.

Supporting walls and other structures which underwent time-dependant shifts are only cracked and damaged to the extent of requiring rehabilitation, but only when the

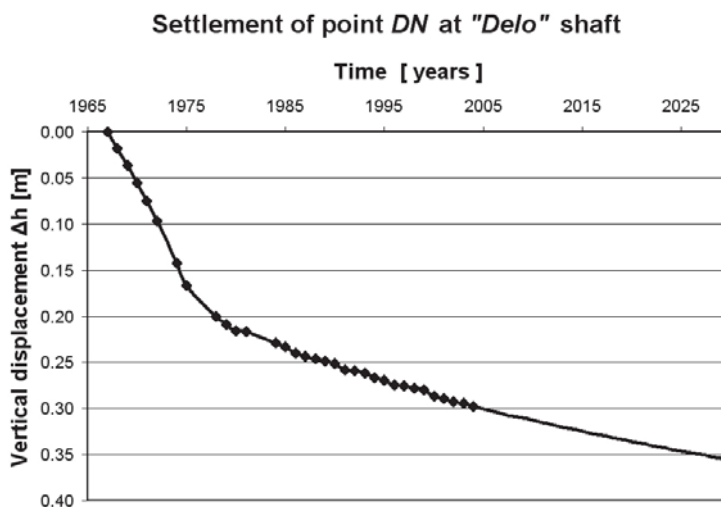


Figure 11. Estimation of the time dependant deformation point DN on the surface above mine

Slika 11. Ocena poteka časovno odvisne deformacije točke DN na površini nad jamo

time gradient of deformations is sufficiently small, or when a sinking rate criterion of less than 1cm/year is attained, which, from the aspect of time prognosis, is still acceptable. Newly constructed structures and rehabilitated facilities will need to be adapted to primary ground shifts.

Prognosis of the development of deformation processes in the long term

The estimation of time-dependant deformations on the surface above the mine has allowed us to prepare a prognosis of the development of the deformation field in the next ten or twenty years. According to the simple logarithmic approximation shown in Figure 11, the sinking of ground in a specific area can be expected to continue for at least 10 years, and therefore the set deformation reduction rate criterion of 1cm/year will be attained after this period.

It should be emphasized that the time frame of shifts in Permian-Carboniferous rocks is more pronounced in comparison with other rocks found in the broader area of the mine. A second threat that is indirectly linked to the sinking of ground is the increased lability of natural and artificial slopes in the southern hinterland of the town of Idrija. Although no major collapses have occurred so far, there have been some occasional minor slides which have had an unfavorable effect on the well-maintained natural surroundings.

CONCLUSIONS

- a) The complex geological composition of rocks in the area of the town of Idrija and the mercury mine, major tectonic occurrences in the broader area, and other geological changes are the principal factors which, alongside mining works, continue to influence the development of deformation fields in the mine and on the surface.
- b) More than five centuries of mining activity in the area of the town of Idrija have caused major changes in the stress deformation states of rocks and backfills in the affected areas of the mercury mine. It has indirectly called for the implementation of measures for improvement of the rock structure and backfills incorporated in the period of intensive mercury ore extraction.
- c) Twenty years ago, extensive numerical models were used to determine the grouted measures to be used within the scope of shutdown works, and laboratory and in situ investigations were conducted in order to determine the geotechnical characteristics of relevant rock strata and artificial backfills.
- d) Observation systems for measuring movements in the mine and on the surface were set up. These included inclinometric and piezometric measurements as well as measurements of stress changes using measurement cells, which are still used today and will continue to be used to a certain extent after the completion of shutdown works.

- e) Time-dependant occurrences of sliding rocks and artificial backfills are still present, yet the intensity of time-dependant movements is considerably reduced and indirectly depends on the speed of filling empty spaces with grout materials.
- f) An evaluation of the adequacy of grouting and backfilling works in the shut-down of the mine has shown that the selected procedures are appropriate for the given geological, geotechnical and mining conditions, and that the long-term stabilization of the broader area will be attained.

POVZETEK

Dolgotrajni deformacijski proces v širšem območju Rudnika živega srebra Idrija

V pričujočem prispevku so podane nekatere posebnosti o izbiri, načrtovanju in načinu izvajanja zapiralnih del v Rudniku živega srebra Idrija. Ker je več faktorjev, ki vplivajo na časovni razvoj deformacijskega polja, so bile pred potrditvijo programa zapiralnih del narejene obsežne študije in strokovne utemeljitve, kar se je kasneje pokazalo kot upravičeno. Predstavljeno in dokazano je bilo, da je zahtevna geološka sestava hribin, ki gradijo območje mesta Idrije skupaj z Rudnikom živega srebra ter izrazita tektonska dogajanja na širšem prostoru in druge geološke spremembe v geološki zgodovini, pomembni vplivni faktorji, ki poleg več stoletij trajajočih rudarskih pridobivalnih del, še danes vplivajo na

časovni razvoj deformacijskih polj v jami in na površini. Tako lahko zagotovo trdimo, da so več kot petstoletne rudarske aktivnosti na območju mesta Idrija pustile za sabo velike spremembe v napetostno deformacijskih odnosih v kamninah in zasipih v vplivnem območju delovanja Rudnika živega srebra ter da je takšno stanje s tem posredno botrovalo utrjevalnim ukrepom hribinskega ogrođja ter zasipov, ki so bili vgrajeni v odkopne prostore v času intenzivnega pridobivanja živosrebrne rude. Z obsežnimi numeričnimi modeli so bili pred dvajsetimi leti utemeljeni utrjevalni ukrepi v okviru zapiralnih del ter narejene laboratorijske in in situ raziskave za potrebe ugotavljanja geotehničnih lastnosti nastopajočih hribin in umetnih zasipov. Za potrebe sprotnega preverjanja časovno odvisnih dogajanj, so bili vzpostavljeni opazovalni sistemi za merjenje pomikov v jami in na površini vključno z inklinometriškimi in piezometriškimi meritvami ter meritvami sprememb napetosti s tlačnimi merskimi celicami. Te meritve se izvajajo še danes in se bodo v dopolnjenem obsegu tudi po končanih zapiralnih delih, saj so časovno odvisni pojavi lezenja kamnin in umetnih zasipov so še vedno prisotni, čeprav je intenzivnost časovno odvisnih pomikov precej manjša ter je posredno odvisna od hitrosti zapolnjevanja praznih prostorov z utrjevalnimi materiali.

Preverjanje uspešnosti utrjevalnih in zapolnjevalnih del pri zapiranju rudnika je pokazalo, da so bili izbrani postopki ustrezni danim geološko geotehničnim in rudarsko tehničnim razmeram, ter da bo dosežena dolgoročna stabilizacija širšega območja.

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