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PROTECTING WIELICZKA SALT MINE AGAINST WATER HAZARD ON THE EXAMPLE OF THE MINA TRAVERSE**

1. INTRODUCTION

In 1978 Wieliczka Salt Mine was put on the UNESCO's World Cultural and Natural Heritage List, as one of the most beautiful objects in the World. Its unique character is connected with the original geological build of the dome, especially the Crystal Chambers, which dazzle with the most beautiful halite crystals, the stunning salt mining technology, well preserved and shown as it was changing over seven centuries, and finally the breath-taking salt sculptures. This place is very attractive to visitors from all over the World. In 2016 it hosted over 1,200,000 tourists.

The Wieliczka Salt Mine occupies an area coinciding with the town of Wieliczka and the neighboring villages. It has a rectangular shape ca. 7 km × 1.5 km. Over centuries, there were drilled 10 levels and 2 interlevels. The total length of the galleries exceeds 200 km, and the volume of workings may reach to even 6.5 mln m^3 [14].

The acquisition of hard salt with mining methods was dangerous, frequently associated with hazard generated by fire, water and methane. Water fluxes to the mine threatened both the mine and also the town over it. The last big flux of 1992 brought about much hazard. For this reason suitable industrial and laboratory investigations had to be undertaken, in the course of which new original technical and technological solutions were worked out. They were used for liquidating the catastrophic water influx to the Mina traverse and the mine protected against any such events in the future.

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2. OUTLINE OF GEOLOGICAL BUILD AND HYDROGEOLOGICAL CONDITIONS

Geologically, the Wieliczka area [4] is built of the Jurassic, Cretaceous (Carpathian flysch), Tertiary (Miocene) and Quaternary beds. Jurassic strata are represented by rocky limestones – compact, hard with numerous silica inserts. Cretaceous beds belong to the Sub-Silesian and Silesian nappe in the form of spotted, grey, grey-greenish slates, interbedded with numerous sandstone layers. The oldest Tertiary beds are sub-saline Skawina beds represented by claystones, marlyclaystones and then evaporate layers in the form of chlorides and sulfides and Chodenice beds (over salt deposit) represented by clays, claystones, marls interbedded with brittle sandstones. Chodenice beds surround the salt dome and their thickness ranges from a few to 500 meters. Bogucice sands underlie the Quaternary beds in the deposit area. The Quaternary beds are composed of Pleistocene and Holocene sediments mainly in the form of loess and clays.

Four basic types of salt can be found in the deposit, i.e. lump green salt, spiza salt, shaft salt and green layered salt. Salt deposit is surrounded by a clayey-gypsum cover protecting it against water. Unfortunately, mining activity disrupted it several times, leading to uncontrollable fluxes of water to the mine.

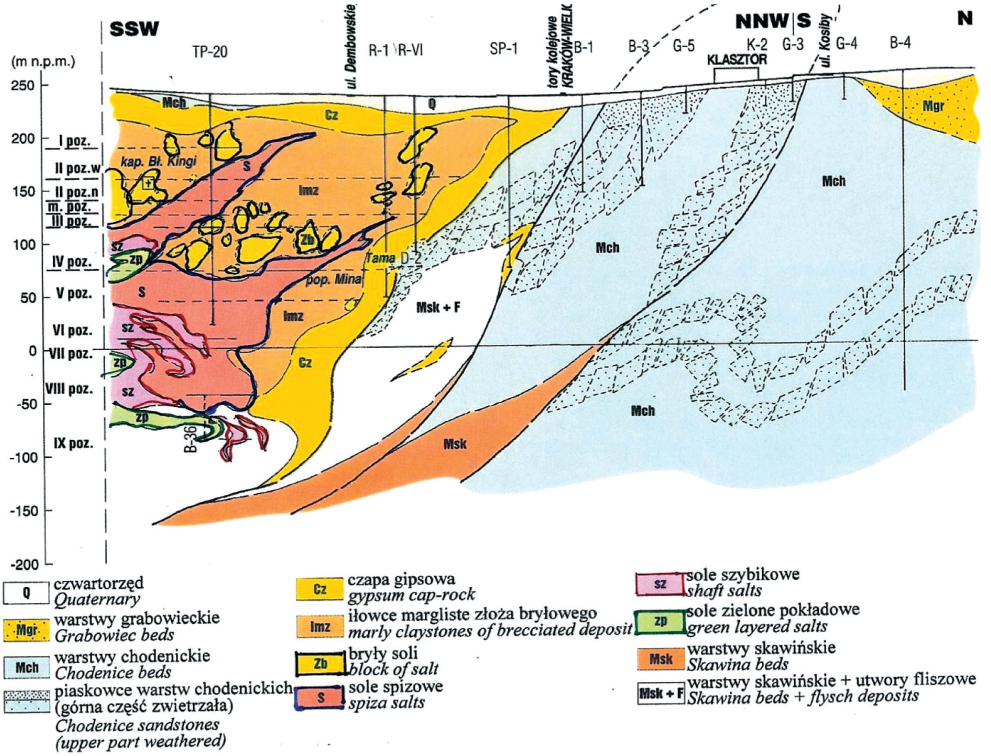


Fig. 1. Cross-section of northern part of the Mina traverse (Szybist)

The isotopic analyses reveal that glacial and Holocene water entered the mine [1, 2], part of the fluxes were glacial water with an admixture of Holocene water, and Holocene water with recent water admixture.

For the sake of illustrating the geological build and hydrogeological conditions, the most hazarded part of the mine was presented in Figure 1.

A more detailed description of the geological setting and hydrogeological conditions can be found in papers by Brudnik et al., Garlicki and Wilk, Garlicki et al. [1, 4, 5].

3. HISTORY OF WATER FLUX IN MINA TRAVERSE

The first section of the traverse (80 m long) between Mirów shaft and Galicja transport ramp was performed before 1815. In the following years it was continued to in the north direction. In the years 1850–53 a section 240 m long was drilled; the face was stopped in the area of the lump green salt (Zuber) deposit. In 1851 the name of the Mina traverse was used for the first time in the documentation. The last, northern section of the traverse was probably performed in 1908–1910. The first information about a water flux in the Mina traverse came from 1935; it says about water rate of 1 l/min and NaCl saturation of 240 g/l. The flux was localized and intaken about 115 m from the northern head of the traverse [14].

In 1989 a project of remaking the final section of the Mina traverse to the flux area was made and labeled as WIV-27. The last section of the Mina traverse started to be reconstructed in 1990 and in the third quarter of 1991 the works was interrupted for financial reasons. At that time the flux flow rate equaled to 4 l/min, and the saturation was 40 g/l NaCl. In the second quarter of 1992 the works in the Mina Traverse were resumed.

On 7 April 1992, when the face of the working was 3.5 m from the end of the old heading, the water flow from the bottom rapidly increased. On 13 April 1992 between 23:00 and 24:00 hrs a rapid flux of water and solid phase was observed in the Mina traverse (about 20 m^3/h). The rescue action was undertaken and timetable of specialist works established. However, on 17 April 1992 another high-rate leak took place, filling the Mina traverse with sediments over a considerable length almost up to its top. In this situation two wells were scheduled to be drilled from the surface to the potential water supply zone responsible for the situation in the Mina traverse. A rescue well R-1 was drilled to 170 m, i.e. to a depth of Mina traverse. It was supposed to play the role of a dewatering well. Pumping water from R-1 did not have any significant influence on the flux in the Mina traverse, where the flow rate still equaled to 500 l/min. On 2 June 1992 the flux to the Mina traverse unexpectedly ceased. On 4 June 1992 it re-appeared at a rate of 200 l/min to completely stop next day at 4:30 hrs. In the period between 5 June and 15 August 1992 the flux stabilized on the level of 0.3 to 1.6 l/min and at a saturation of 50 g/l NaCl. This period was used for elevating a three-segment water dam consisting of a block dam, clay dam and concrete dam in the Mina traverse. A number of injection wells were performed around the concrete segment, then cement slurry was injected to reinforce the rock mass around the dam (Fig. 2). For doing so, a pipeline was installed in the dam, which was used for discharging water gathering behind the dam. At that time the leak oscillated between zero to 5000 l/min. After closing the pipeline on 9 September1992 due to the increase of water pressure behind the dam, numerous leaks were observed behind the discharging pipe, and then from above the dam and caverns localized a few meters before the dam. A rapid flux of considerable quantities of water and solid phase from the surrounding rock mass omitted the newly erected dam, and formed the eastern, western and northern cavern before it (Fig. 2). This was the second catastrophic water flux in the traverse of such a magnitude that the consequences could be seen on the surface in the northern forefield of the Mina traverse.

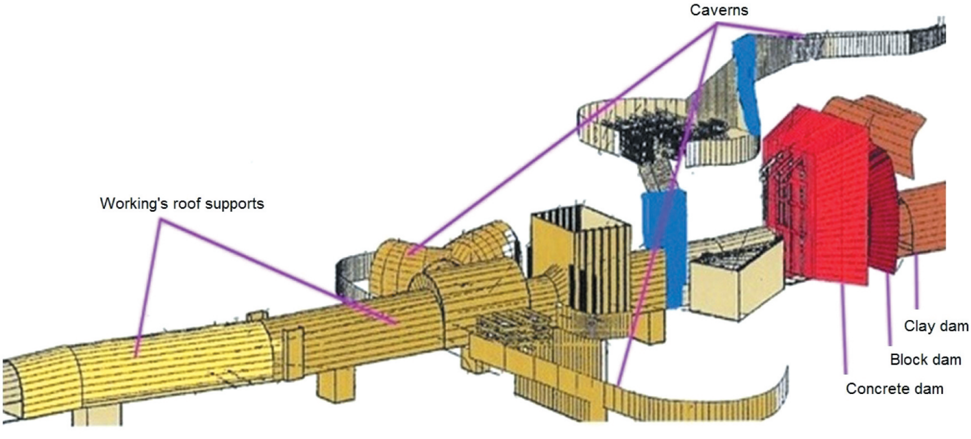


Fig. 2. Schematic of protection applied to the end part of the Mina traverse

Fig. 3. View on the railway tracks and stone fence around the cloister

On 11 September 1992 a subsidence trough was observed on the surface. First the maximum subsidence equaled to 0.3 m but gradually increased to finally exceed 2 m. Apart from it, under the influence of the underground movement, the railway tracks were distorted on the Wieliczka – Wieliczka Market route, as in (Fig. 3), and part of the stone fence around the Franciscan Cloister got destroyed, too. Dangerous cracks appeared on the walls and the ceilings of the cloister, threatening the stability of the object (Fig. 4).

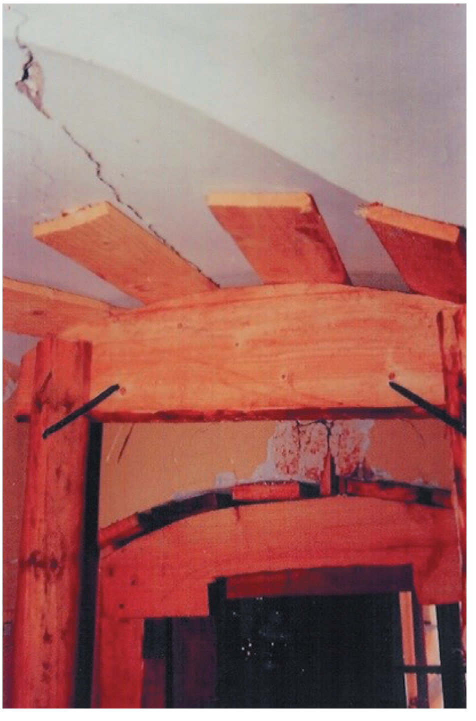


Fig. 4. Fragment of supported roof in the cloister

4. WORKS PROTECTING THE MINE AFTER THE SECOND DISASTROUS WATER FLUX TO THE MINA TRAVERSE

Works connected with working out an efficient method of sealing the rock mass, which would eliminate water flux to any salt mine were extremely difficult. This was connected with the solubility of salt and the impact of the formed brine on the rock mass and sealing slurries. However, before all, there were no positive examples of protection of salt mines on World's scale.

The initial works connected with the liquidation of catastrophic fluxes to the Mina traverse lied in performing a filtration membrane from the surface in the area of potential place of leak in the rock mass [3].

The filtration membrane realized with the use of two wells drilled from the surface north of the gypsum-clay protection of the deposit was to seal the rock mass, and so fill the fractures and voids with properly selected sealing slurry.

By the end of 1992, 8 injection wells were drilled; they confirmed the existence of voids in the rock mass above the Mina traverse and because of their low efficiency, their realization was ceased.

Another stage lied in the liquidation of the ends of the Kunegunda traverse and Poniatowski traverse, localized on level II and III [11] and level V of the inaccessible Badeni traverse, localized almost above and under the Mina traverse. The potential flux directly threatened the Tourist Route and the associated objects, constituting a serious hazard for the entire Wieliczka Salt Mine.

This problem was solved with an original method, i.e. pipeline injection method [10]. Sealing slurry was prepared on the surface and injected through a pipeline to the shaft to the workings to liquidate the traverse ends. This solution was chosen for a number of reasons:

- the traverse ends were at a considerably distance from the shaft,
- no transport tracks to the traverse,
- dimension and localization of the traverse in the mine.

Another very important problem to be solved was a recipe of the sealing slurries which would have appropriate rheological parameters, regulated time of bonding, strength, adhesiveness to Wieliczka rock mass, high resistance to corrosive impact [18].

About 342 m^3 of slurry was injected to the Poniatowski traverse and about 450 m^3 to the Kunegunda traverse [11]. The end of Badeni traverse (under Mina traverse) was liquidated by a series of drilled injection-dewatering wells from the bottom of the Mina traverse [12]. Over 250 m^3 of sealing slurry was injected in this way protecting the direct neighborhood of the Mina traverse, where water (partly salted) with different solid phase content, continued flowing in.

At the next stage water from behind the dam was discharged through special drainage boreholes D-1, D-2 and D-3 drilled through the dam towards the R wells [6]. These boreholes were drilled in 5 m long zones; then they were injected with the slurry to restore the northern protection layer directly behind the water dam. They were maximum 70 m long.

Owing to the complex spatial build of the Mina traverse end and various hydraulic communication pathways between caverns, the reinforcement and sealing of the rock mass were done in stages:

- Dunajewski gallery from dam T-4,
- from dam T-4 to dam T-1 with exploration heading and its off-shot,
- from dam T-1 to water dam [7].

In view of the safety of miners, the following solution was proposed for the T-4 to T-1 section (Fig. 2):

- first build a steel tunnel,
- fill the space between the rock mass and the steel tunnel with sealing slurry,
- drill directional boreholes and perform zonal injection through them.

For the section leading to dam from dam T-1 to water dam the following was proposed:

- introduce injection and dewatering pipelines to the northern cavers to fill it with the sealing slurry,
- drill H-series directional boreholes and conduct zonal injection through them: I, II and III, respectively.

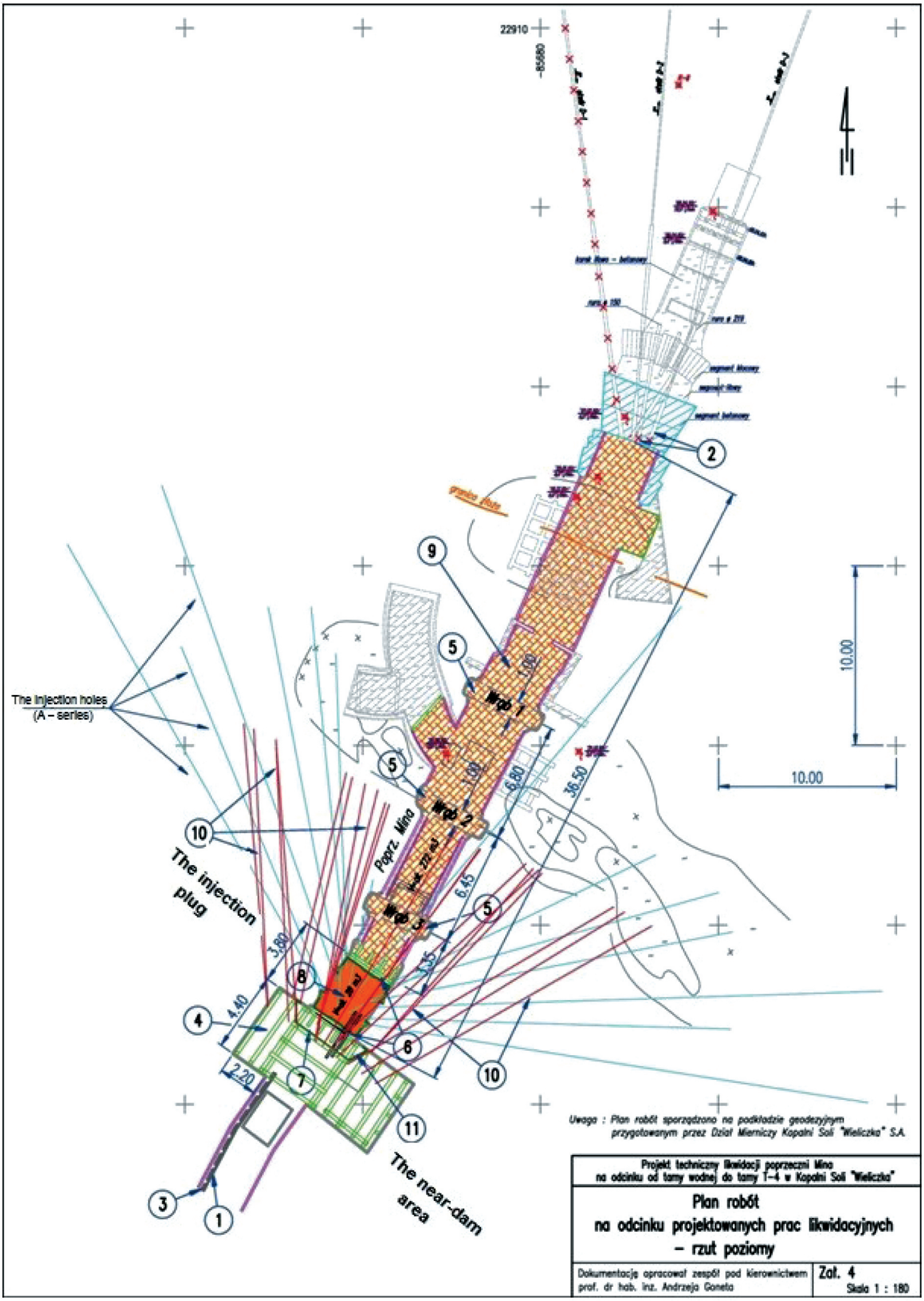
The drainage well D-2, localized in the water dam and ending in the northern forefield of the salt deposit, received discharge water for the longest time. Periodically the flow in D-2 was selfactedly clogged. Two other drainage boreholes D-1 and D-3 in the dam were used for receiving water and for measuring water pressure behind the dam. For presenting the character and amount of water, as well as solids and salts flowing into the mine, plots were prepared [14]. They were based on the current monitoring data. Generally, the yield of the leak WIV-27 was high and the NaCl concentration was low as for a salt mine. This proved that the circulation pathways in the salt rock mass were short and the flow rate was high. This type of flux create a very serious dangerous for each salt mine.

The considerable water stream was running pulsatingly at small depths, carrying solids and dissolved sale from the forefield to the mine. As a result voids were formed in the rock mass. This was confirmed by geophysical surveys and besides a subsidence trough over 2 m deep was formed on the surface. On the days of the catastrophic flux occurrence, considerable cracks could be also seen in the cloister hill. The mine and the Wieliczka area in the north part of the salt deposit were additionally protected from the surface [9]. They were aimed at:

- filling the fractures in the cloister hill [15],
- filling the voids in the rock mass in the neighborhood of the subsidence site,
- partial filling and reinforcing of the water discharge pathway from the southern subsidence site to the Mina traverse area.

The works were undertaken on 4 May 1993 in SP-1 well [17], which was drilled as a piezometric well for the exploration well TOS-1, and then in TOS-1. Both these wells were periodically injected with predefined portions of sealing slurry and in the final stage both these wells were closed and the neighboring rock mass was significantly reinforced.

The reinforcing and sealing of the rock mass and the Mina traverse ends [8] are schematically presented in Figure 5.


The injection holes
(A – series)
The injection plug
The near-dam area
Wrob 1
Wrob 2
Wrob 3
Poprz. Mina
10.00
10.00
36.50
6.80
6.45
3.80
4.40
2.20
22910
Uwaga : Plan robót sporządzono na podkładzie geodezyjnym przygotowanym przez Dział Mierniczy Kopalni Soli "Wieliczka" S.A.
Projekt techniczny likwidacji poprzeczni Mina na odcinku od tamy wodnej do tamy T-4 w Kopalni Soli "Wieliczka"
Plan robót na odcinku projektowanych prac likwidacyjnych – rzut poziomy
Dokumentację opracował zespół pod kierownictwem prof. dr hab. inż. Andrzeja Goneta
Zał. 4
Skala 1 : 180

After performing hole injection in the Mina traverse end, the probable range of sealing is as shown in Figure 6.

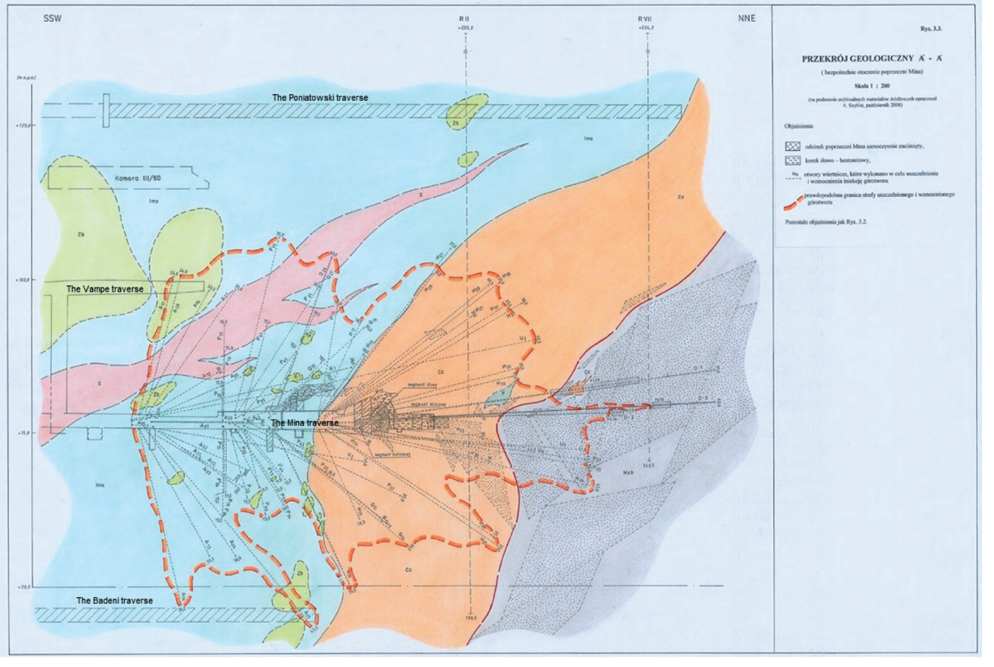


Fig. 6. Geological cross-section with injection holes and marked zone of potential range of rock mass sealing [8]

Above discussed works were aimed at performing a sealing cap, i.e. reinforcing and sealing of the safety pillar in the northern part of the salt deposit in the Mina traverse area.

Fig. 5. Plan of works in the Mina traverse end 1 – providing master injection pipeline to Mina traverse (close to drilling cavity), 2 – liquidation of drainage wells D-2 and D-2, dismounting of redundant pipelines and equipment (in the liquidate Mina traverse section), 3 – preparation of a pipeline discharging brine from washing of master pipeline, 4 – increasing of existing cavity to the west side of the Mina traverse, 5 – dismounting of existing traverse supports in the place of planned cuts, making cuts to intact rock mass, 6 – dismounting of the existing part of the traverse supports in the place of the planned injection plug, building of timber dams for making injection plug, 7 – building of the near-dam area, 8 – tight filling of the injection plug with special slurry, closing of the plug, 9 – dosing of special slurry to liquidate the working behind the injection plug, till it is completely filled, 10 – drilling sealing-up wells (S-series) and sealing up the rock mass around the plug with the injection method, liquidation of sealing-up holes, 11 – dismounting of the near-dam area [8]

Many years' protection works [6, 7, 10, 15, 16, 18] conducted with various intensity, were closely related with the financial aspects. On 15 October 2007 the gate was closed in the last drainage well and so the influx to the Mina traverse ceased. Summing up the inflow in figures [2], from 13 April 1992 we have:

– total influx from the leak – 1,037,596 m^3,
– carried solids – 64,089 Mg,
– NaCl brought by water – 10,635 Mg.

5. CONCLUSIONS

1. The geological setting of the Mina traverse area is very complex. From the north, behind the clayey-gypsum cover, there are Chodenice beds, where considerable amounts of pressurized water accumulate, creating biggest hazard for the Wieliczka Salt Mine.
2. The major causes of water leaks in the Wieliczka Salt Mine are:
   – unfavorable geological and hydrogeological conditions behind the northern boundary of the salt deposit,
   – many years' mining activity in the clayey-gypsum cover, make it thin out, lose strength and increase permeability, consequently leading to the loss of stability.
3. The catastrophic water influx to the Mina traverse was liquidated after undertaking multidirectional activities realized from the surface and from the workings' level. Thanks to the applied modern technologies of hole and pipeline injection as well as original recipes of sealing slurries, the influx could be managed and the mine in the Mina traverse area and all damaged sites protected, restored and revitalized.

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