

ANDRZEJ GONET¹, STANISŁAW ANTONI STRYCZEK¹***INNOVATIVE TECHNOLOGY OF TIGHT LIQUIDATION OF WORKINGS
ON THE EXAMPLE OF THE WIELICZKA SALT MINE**

The authors of the paper describe the way in which the longitudinal working Gussmann was mined in level V and the longitudinal working Kosocice in level VI, which in both cases resulted in a water flux from behind the northern boundary of the salt deposit. Only after concrete dams were seated on both levels, the brine flux was stopped leaving a direct contact of the dams with the pressurized water around the mine. For the sake of controlling water beyond the dams, steel pipelines were conducted through both dams and equipped with gauges before the dams. Their use in a saline environment, the developing corrosion increased the possibility that the tightness of the pipelines would be damaged. For this reason a decision was made to protect the mine by making a tight reconstruction of the safety pillar in both levels along the longitudinal working for about 600 m from the dams eastwards. For this purpose the pipeline injection method was applied. As the volume of voids to be tightly filled equaled to about 3800 m³, the task had to be divided into stages. Because of considerable distances of the liquidated workings from the closest shaft, the sealing slurries were prepared in a special injection center on the surface from where they were transported to the destination with a pumping pipeline through the Kościuszko shaft. The most important aspect of liquidating the end parts of the longitudinal working was to properly select the sealing slurries in view of their best cooperation with the rock mass, and such parameters as tightness, durability and cost. At the end stage of works, both longitudinal workings were equipped with dams, which were sealed up with the hole injection method. The innovative technology was implemented in the Wieliczka Salt Mine to reconstruct the safety pillar in levels VI and V in the most westward workings, the mine was shortened by about 600 m, the length of the ventilation system was reduced, systematic observations and pressure read-outs in dams 3 and 4 were systematically eliminated in dams 3 and 4. In this way the costs were lowered and safety of the mine improved.

Keywords: salt mine, water hazard, safety pillar, Wieliczka

¹ AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF DRILLING, OIL AND GAS, AL. A. MICKIEWICZA 30, 30-059 KRAKOW, POLAND

* Corresponding author: gonet@agh.edu.pl



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1. Introduction

One of the most important parameters as far as mines are concerned, is their safety. An original technology of safety pillar reconstruction was presented in the paper on the example of longitudinal workings Gussmann and Kosocice in the Wieliczka Salt Mine. For preserving its unique character as the World's scale object, Wieliczka Salt Mine had to be properly protected against water hazard. Over seven centuries of mining activity resulted in the formation of over 6 million m³ of voids and about 220 km of workings. One of the elements of such a complex program was the liquidation of western ends of the longitudinal working Gussmann in level V and longitudinal working Kosocice in level VI. In this way the inner safety pillar could be reconstructed and workings in the western part of the mine reduced by about 600 m. Formerly many works were realized without detailed pre-recognition of geological and hydrogeological conditions which consequently resulted in some damage to the safety pillar and water leaks in the mine and beyond its area. Several times the mine was threatened with floods and the last time was the catastrophic flux from the transverse working Mina in level IV at 170 m b.s., which started on 13 April 1992. Numerous prevention measures have been applied for years since then (Garlicki et al. [5], Gonet et al. [8], Stryczek, Gonet [10]). Their intensity mainly depended on the financial condition of the mine. Finally the gate on the last drainage well D-3 in the transverse working Mina was closed on 15 Oct. 2007. The total balance of the flux (d'Obyrn, Brudnik [2]) to the mine of 13 April 1992 was the following:

- leak – 1037596 m³,
- amount of carried solids – 64089 Mg,
- amount of NaCl introduced by leak waters – 10635 Mg.

2. An outline of geological build and hydrogeological conditions

The salt deposit Wieliczka has an approximately rectangular shape 7 km × 1.5 km. Its geological build is very complex (Garlicki, Wilk [6]): Jurassic and Cretaceous beds (Carpathian flysch), Tertiary beds (Miocene) and Quaternary beds. Four basic types of rock salt are present there, i.e. green lump salt, spiza salt, shaft salt and green layered salt. The salt deposit is insulated with a clayey-gypsum cover which efficiently protects it against the surrounding water. Unfortunately the cover was disturbed with mining activities which led to an uncontrollable water flux to the mine. The isotopic analyses reveal that water leaks invading the mine (d'Obyrn, Brudnik, [2]) consist of glacial water and holocene water; part of the leaks are glacial water with an admixture of holocene water and holocene water with an admixture of recent water.

3. Innovative technology of safety pillar reconstruction on the example of longitudinal workings Gussmann and Kosocice

In 1866 potassium-magnesium resources accompanying rock salt were searched for. After two years of mining the transverse working Kloski in level V, a catastrophic water flux occurred flooding nearly completely workings in level VI. Water was controlled only in 1879. The same

idea stood behind mining works in the longitudinal working Gussmann in level V and longitudinal working Kosocice in level VI. In both cases the passability of water beyond the northern boundary of the salt deposit was restored. Special attention should be paid to the boundary safety pillar where the potentially watered gypsum-clayey cover may contact the adjacent formation, i.e. spiza salts. In 1959 the workings in levels V and VI, which pass through the cover, were filled with brine from behind the gypsum-clayey cap. Only after building concrete dams on both sides the water inflow to the mine was stopped, leaving an open contact of the dams with water around the mine. In turn, dams closing workings 3 and 4 were seated in saline, not clayey rocks. This increased the risk of damaging their water tightness. The behavior of the described mine workings is basically characterized by uniaxial compressive strength, tensile strength, cohesion, inner friction angle, Young modulus and Poisson number (Cała at al. [1], Flisiak, Cyran [4]). These values are given in the form of intervals because of the diversified geological build of the mine and differing watering of rocks (d'Obyrn [3]). The following values can be given for both ends of longitudinal working basically built of spiza salts:

- strength to uniaxial compression 23.5 to 53.0 MPa,
- tensile strength 0.9 to 11.9 MPa,
- cohesion 3.3 to 11.3 MPa,
- inner friction angle 9.6 to 71.0°,
- Young modulus 1000 to 1820 MPa,
- Poissona number 0.4 to 0.48.

For controlling the pressure of water beyond the dams, pipelines were conducted through them and gauges installed before the dams. Owing to the similarity of the described effect, only the end part of the longitudinal working Gussmann in level V was presented in photo 1.



Photo 1. Water dam with dewatering pipeline and gauges in the longitudinal working Gussmann in level V

Water pressure beyond the dam in the longitudinal working Gussmann usually exceeded 0.42 MPa and the brines had negatively affected steel pipes and concrete dam for years. Their technical condition deteriorated which can be evidenced by dampness of the dam and corrosion of the pipes. A similar situation was found at a concrete dam in level VI, though in this case the water pressure on the gauge was 0.81 MPa. For the sake of mine's safety the condition of the pipeline and water pressure should be periodically checked and ventilation constantly provided to the most westward part of the mine. For eliminating the risk of infiltration of rainwaters and brine from the borehole mine Barycz through the boundary pillar between Barycz and Wieliczka mines, and potential flooding of the workings of the historical Salt Mine Wieliczka, pipelines going out from beyond dams 3 and 4 had to be efficiently closed. The brine beyond the concrete dams had to be moved out, and the sections of underground workings in levels V and VI in the vicinity of the pillar between the mines liquidated. According to Zuber and Szczepański failing to apply such measures might result in further uncontrollable and catastrophic water fluxes. If such activities were applied, the safety of the Wieliczka mine in its western part would be increased. The pillar separating the Barycz and Wieliczka mines would be broadened and emergency fluxes in the vicinity of chamber Z-32 minimized. The end parts of the longitudinal working Gussmann and longitudinal working Kosocice belong to the methane hazard category I and water hazard category III, therefore all works conducted in that area should be realized in line with the respective regime. For minimizing the potential water hazard and lowering the cost of further operation of the mine, a decision was undertaken to close ends of both longitudinal workings located at the salt deposit boundary, and so tightly reconstruct the safety pillar (Gonet et al. [7]). Pipeline injection method was selected for this purpose as this technique was most efficient for tight filling workings located at a greater distance from the shafts. The nature of this technology has been illustrated in figure 1 and described in detail in patent AGH-UST no. PL 170267.

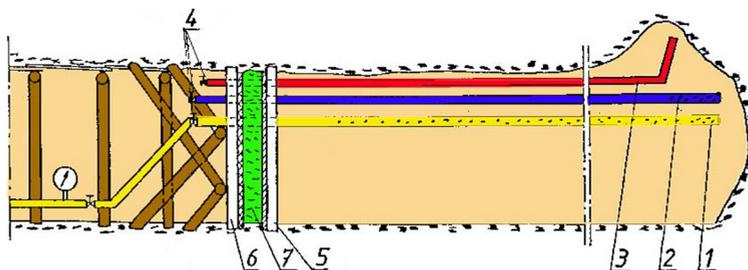


Fig. 1. Schematic of closing end part of working with the pipeline injection method
 1 – pumping pipeline, 2 – vent-pumping pipeline, 3 – vent pipeline, 4 – gates, 5 – inner dam,
 6 – outer dam, 7 – injection plug

Owing to the considerable volume of voids (3800 m³) to be filled, the whole job was divided into stages to minimize the cost of realization of the entire undertaking. Moreover, owing to considerable distanced of workings to be liquidated from the nearest shaft and difficulties with transport of such huge amounts of material for the production of sealing slurry, the sealing slurries were prepared in a special injection center (photo 2) located on the surface and providing the slurry to the destination with and pumping pipeline through the Kościuszko shaft. Smaller amounts of slurries to be injected beyond dams 3 and 4 were prepared in the mine.



Photo 2. New injection center

With the inventory documentation worked out by the Measurements Department KSW and taking into account the minimization of costs of prevention measures, only 3 injection plugs and 2 end dams were designed on both ends. Owing to its considerable length, two injection plugs were designed in the longitudinal working Gussmann, and the planned dams were located in the vicinity of one vertical plane. This means that the volume of tightly filled workings in one operation totaled to 1100 m³, which was unprecedented on the Polish and probably also World's scale. For this reason all preparatory works had to be performed professionally on the highest quality level. This especially applies to the pumping pipelines, vent-pumping pipelines and vent pipelines, injection plugs and end dams.

It was important for the prevention works performed in the Salt Mine Wieliczka to properly select the sealing slurries (Stryczek, Gonet [10]). Their composition was analyzed mainly in the aspect of:

- best cooperation with complex rock mass,
- tightness and durability,
- cost.

As a result a decision was undertaken to apply a slurry based on fully saturated brine and granulated blast furnace slag, supplemented with cement CEM I 42,5R, sodium carbonate and appropriate water-to-mixture index. This slurry was patented under the number PL 171213. After conducting laboratory analyses encompassing a broad range of technological parameters, six recipes labeled as A1 to A6 were selected for practical application (Table 1).

Particular slurries were laboratorily analyzed on with a viscometer Chann 35, and the obtained results were statistically worked out to fit the best rheological model. An exemplary yield curve of saline slurry flow described with the Bingham model, is presented in figure 2.

TABLE 1

Recipes and bonding times of sealing slurries in temperature 20° (±2°C)

Slurry denotation	Sealing slurry components per 1 m ³				Water/mixture ratio w/m [-]	Density of slurry [kg/m ³]	Bonding time [hrs]	
	Working fluid (brine) [dm ³]	Cement CEM I 42,5R [kg]	Na ₂ CO ₃ [kg]	Ground granulated blast furnace slag [kg]			Beginning of bonding	End of bonding
A1	558	140	0	1255	0.48	2030	8 h 50 min	13 h
A2	558	110	30	1255	0.48	2020	3 h	6 h 40 min
A3	612	123	0	1100	0.60	1960	11 h 10 min	16 h 20 min
A4	612	100	23	1100	0.60	1950	9 h 10 min	14 h 15 min
A5	715	45	0	850	0.96	1830	33 h	42 h
A6	715	65	25	805	0.96	1820	27 h	40 h

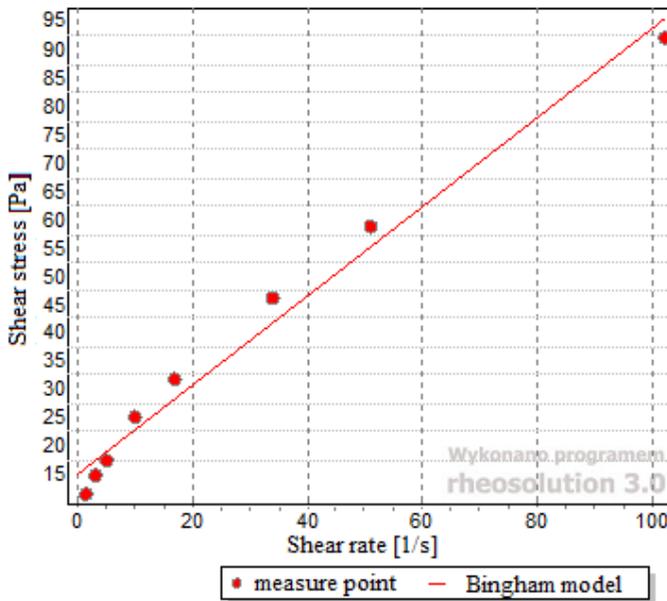


Fig. 2. Yield curve for saline slurry described with Bingham model

In this model the flow resistance of slurry in the pipeline was calculated with the following formulae:

– for turbulent flow:

$$p = \frac{2fL\rho}{d} v^2 \tag{1}$$

– for laminar flow:

$$\Delta p_r = \frac{32L\eta_p}{d^2} v + \frac{16}{3} \frac{L\tau_y}{d} \quad \text{if } S \leq 14 \quad (2)$$

$$\Delta p_r = \frac{47,128L\eta_p}{d^2} v + \frac{4,242L\tau_y}{d} \quad \text{if } S > 14 \quad (3)$$

where:

- τ_y — yield point; Pa,
- η_p — plastic viscosity; Pas,
- ρ — density of saline sealing slurry; kg/m³,
- d — inner diameter of pumping pipeline; m,
- f — Fanning friction loss factor; -,
- L — length of pumping column; m,
- v — average velocity of saline sealing slurry; m/s,
- S — Saint Venant number; -.

$$S = \frac{d\tau_y}{v\eta_p} \quad (4)$$

Each type of slurry had its own applicability: slurries A1 and A2 for injection plugs, A2 and A3 for end dams, A1, A3 and A5 for filling voids, A4 and A5 to be injected beyond water dams 3 and 4, A5 and A6 for borehole injection at end dams in levels V and VI. Above recipes were modified in practice according to the author's supervision program, depending on the encountered rock mass conditions.

At the first stage of works the construction of the pipelines structure under dam 4 in level VI was verified:

- steel pipeline 100 mm in diameter and 3.7 m long,
- gate for 4.0 MPa,
- gauge to 2.5 MPa,
- electronic gauge,
- reduction of the pipeline from 100 mm to 80 mm diameter with a gate for a pressure up to 2.5 MPa.

At the second stage, the following elements were installed before dam 3 in level V:

- steel pipeline 150 mm in diameter and 0.65 m long,
- gate for 4.0 MPa,
- gauge to 0.6 MPa,
- electronic gauge,
- gate for 2.5 MPa,
- reduction of the pipeline to 80 mm in diameter and 1.15 m in length.

After analyzing water pressure indications from beyond the dams recorded by gauges installed in the pipelines before the dams in a longer time perspective and after preparing materials, equipment and devices for the injection job in a given spot, the electronic gauges were replaced with classic ones up to 2.5 MPa in levels VI, and up to 1.6 MPa in level V. After checking the

technical condition of all machines and devices, a pump WT-30 responsible for pumping sealing slurry beyond the dam, was installed to the pipeline. Slurry was prepared in a mixer located at the end of the longitudinal working in compliance with the recipes. In this case recipes A5 and A4 were applied. As the conditions beyond the dams were not known, the injection technology had to be established according to the author's supervision program.

Two alternative limitations were assumed for the sealing slurry:

- injection of 5 m³ of slurry,
- pressure of 1.6 MPa is to be maintained for 30 minutes in level VI, i.e. at dam 4 and pressure 1.2 MPa in level V, i.e. at dam 3.

After meeting these criteria, the gates were closed on the pipelines and water level indications observed in piezometer PZ-1 in the forefield of the Salt Mine Wieliczka, at the western ends of liquidated workings.

4. Technology of filling ends of the longitudinal working

The number of the liquidated working-ends was high, therefore the whole job was divided into stages. The major works at each stage were focused on:

- preparatory works, different at different stages, depending on the present condition. For providing tightness and efficiency of works, cuts to the intact rock mass were performed every 50 m around the working,
- system of pumping pipelines, vent-pumping pipelines and vent pipelines in selected parts of the longitudinal working. Pumping pipelines and vent-pumping pipelines were locally perforated; vent pipelines were not perforated and their ends were placed in the liquidated part of the longitudinal working,
- tight injection plugs ending the 3rd, 5th and 7th stage of work,
- sealing slurry is injected into specified parts of workings till they are filled up,
- constructing end dams in levels VI and V,
- sealing up end dams and the surrounding rock mass.

The injection of the sealing slurry into the specified space of longitudinal working could be stopped when sealing slurry started to flow through the vent pipelines, evidencing that the whole void beyond the dam was filled. Each section of the liquidated working was separated with an individual injection plug localized in these places in which the surrounding rock mass was the strongest. Each injection plug was at least 3.0 m long, and the inner space was tightly filled with slurry. For technological reasons, a low dam was performed before each injection plug and end dam at a distance of 1.0 m on the whole width of the working and 0.8 m high.

A similar arrangement was applied to the end dams. The only difference was that they were over 5.0 m long, and the surrounding rock mass was sealed with the borehole injection method. Each of the injection holes was 10 m long and a casing 2 m long. The first boreholes were drilled at an angle of 15° with respect to the side of the working, the second boreholes were inclined at 30°. In each sealing 'ring' there were drilled for 6 boreholes shifted with respect to each other by 60°. The boreholes drilled in the first and in the second ring were shifted by 30°. The borehole was drilled 2 m deep with a 115 mm drill, next the casing 100 mm in diameter was tripped with centralizers and sealed with slurry over its whole length. After a tightness test, the drilling was continued by zones, each 4 m long. Slurry was injected to generate pressure of 1.6 MPa in

level VI and 1.2 MPa in level V for 30 minutes. The injection job was stopped when the slurry got into the working. After a break in which the slurry was bounded, the works were continued.

The inventory analysis of the volume of sealing slurry injected at particular stages of work is as follows:

- 10 m³ to be injected beyond water dams 3 and 4 (by 5 m³ each) – stages 1 and 2,
- 20 m³ to fill the first injection plug in longitudinal working Gussmann – stage 3,
- 1055 m³ to fill the first section of longitudinal working Gussmann – stage 4,
- 20 m³ to fill the first injection plug in longitudinal working Kosocice – stage 5,
- 1107 m³ to fill the first section of longitudinal working Kosocice – stage 6,
- 20 m³ to fill the second injection plug in longitudinal working Gussmann – stage 7,
- 1040 m³ to fill the second section of longitudinal working Gussmann – stage 8,
- 30 m³ to fill the end dam of longitudinal working Kosocice – stage 9,
- 284 m³ to fill longitudinal working Kosocice – stage 10,
- 30 m³ to fill the end dam of longitudinal working Gussmann – stage 11,
- 214 m³ to fill longitudinal working Gussmann – stage 12,
- 48 m³ to seal end dams with borehole injection – stages 13 and 14.

This amount of sealing slurry could be produced from about 1800 m³ of fully saturated brine. It should be also stressed that after each instance in which the pipeline injection method was used, the pumping pipeline had to be thoroughly flushed from the Kościuszko shaft to the end dams to remove the solids from the slurry. This means the demand for brine was higher by about 100 m³. The assumed goals were accomplished so safety pillar could be restored in levels VI and V in the westernmost workings. The mine was shortened by about 600 m and the length of the ventilation system reduced. The systematic observations and read-outs in dams 3 and 4 were eliminated. Finally, the cost was lowered and the safety in the mine increased.

5. Conclusions

1. As a consequence of poor geological and hydrogeological recognition, the prospecting works for potassium-magnesium salt deposits ended in a flux of water in 1959. Water invaded the western ends of longitudinal working Gussmann and longitudinal working Kosocice from beyond the mine.

2. The end of longitudinal working Gussmann in level V and longitudinal working Kosocice in level VI belonged to the methane risk category I and water hazard category III, therefore all jobs performed in that area had to follow the rules associated with these hazards.

3. For improving the efficiency of closing end parts of workings in levels V and VI, it was decided to remove pipelines coming from beyond water dams 3 and 4. Their liquidation lied in injecting sealing slurry, 5 m³ each. Slurry filled the pipeline and the immediate surrounding of the flooded workings beyond the dams.

4. For the sake of monitoring the hydrogeological conditions in the end parts of longitudinal working Gussmann and longitudinal working Kosocice, a piezometric well PZ-1 was designed.

5. Assuming the minimization of the cost of all works for filling the longitudinal working and for sealing the rock mass around them was made of ground granulated blast furnace slag, cement CEM I 42,5R, sodium carbonate and fully saturated brine. Six various recipes were used for jobs performed in particular stages.

6. Due to technological limitations and considerable volume of voids (about 3800 m³) to be tightly filled, the job was divided into 14 stages including:

- preparatory works completed with the construction of pumping pipelines, vent-pumping pipelines and vent pipelines,
- injection plugs (1 in level VI and 2 in level V) as end dams in both levels,
- injection of sealing slurries (2 portions in longitudinal working Kosocice and 3 portions in longitudinal working Gussmann).

The order of jobs corresponded to the increasing number of stages.

7. After performing end dams, they and the surrounding rock mass were sealed with the borehole injection method. Two ‘rings’ of boreholes were drilled, with 6 boreholes in each ring. The boreholes were shifted by 60° with respect to each other and by 30° in particular rings.

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