A new method of regulating the load on the shaft lining in sections passing through the salt rock mass

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Abstract: Rock salt is characterised by specific geomechanical and rheological properties. The layers of rock salt which occur on the depths over 900 m contribute to problems with shaft lining deformation. Methods of shaft lining protection used so far (e.g. in Sieroszowice mine) have not been effective enough. The research presents a patented and copyright protected concept of constructing a shaft lining that goes through rock masses having strong rheological properties and being susceptible to leaching. In the case of salt layers, especially at significant depths the relative convergence of the heading contour may amount to 40 ‰/year. That results in the fact that any other method of securing the shaft lining, e.g. by making it flexible, will not be sufficient to ensure the stability of the shaft reinforcement geometry. In the new shaft lining concept the excessive rock creep into the outbreak inside the shaft diameter will be removed by local and controlled leaching of the shaft cheeks by means of fresh water directed through a porous medium at the contact layer behind the watertight tubing lining.

Keywords: mining shaft; salt rock; leaching

1. Introduction

Convergence of the salt rock sidewall generates very strong pressures inserted onto shaft lining (Lotze, 1957; Schuppe, 1966; Höfer i Thoma, 1968; Serata, 1968; Ślizowski, 2001). Convergence rate is an indicator informing us what action should be undertaken in order to reduce its destructive influence for the shaft lining.

As was proved by professional calculations and observations conducted on a section of the salt rock sidewall, that rheological deformations in the salt rock can cause excessive load of the final shaft lining in relatively short time (Flisiak 2005, Fabich 2016). Modification of the shaft lining in active shaft is rather impossible, with respect to necessity of the shaft operation stoppage for long time period. Thus designing of the shaft lining assuring removal of the creeping salt rock from the shaft, is necessary.

As the salt is easily soluble in freshwater, contact of salt body on the whole surface with water introduced into this space should be assured. As the salt is easily dissolved in freshwater, contact of salt body on the whole surface with water introduced into this space should be assured in the new construction of the shaft lining. Saturated solution developed in result of the dissolution should be removed from the space of shaft lining. As was proved by the experiments, stagnant water should be periodically replaced or thinned with freshwater, or recycled in form of laminar or turbulent flow. Thus the space between final shaft lining forming internal cylinder and the shaft sidewall should be such organized that it fulfilled two functions in the same time:

a) Enabling load transfer from the rock body onto shaft lining,

b) Enabling controlled flow of freshwater behind final shaft lining.
New construction of the shaft lining called as “tubing-aggregate lining” comprises the following elements:

1. Preliminary roof bolting protecting shaft pipe, during going from the top to the bottom via salt rock body layer

2. Tubing cylinder of the tubing lining installed from the bottom to the top, which is supported on special technological ring localized right under the floor of the salt rock layer.

3. Special construction of tubing being technological rings of individual sections of the shaft lining, of the length determined only by examinations made on testing section made in one of the shafts sank in this region.

4. Filling with porous material – coarse grained aggregate of high compression strength, allowing temporal washing of the salt rock sidewalls with freshwater or salt brine of suitably selected concentration.

5. Pipe-line systems, pumps and containers for leaching medium and salt brine inflow and outflow.

The aggregate used in the described solution has a key task, as it must assure contact between salt rock body and shaft lining. Moreover, it should constitute porous structure, which could be freely penetrated by leaching medium. In addition is plays a role of the deformable and equalizing layer for point loads.

2. Device for salt rock leaching

A number of tests and analyses were planned in order to prove assumed thesis. The first examination series was additionally aimed for verification of the device operation and calibration.

Differentiation of executed tests can be described by the following factors:

a) Water temperature and salinity,

b) Size of the cross-section and sample preparation procedure,

c) Contact of the salt with aggregate,

d) Character of the acting load,

e) Volume of the leaching medium and flow characteristics.

30 the most representative samples have been selected and registered results were exposed to further analysis. Cube-shaped and rectangular-shaped samples were cut from the salt material, and the samples characterized with the cross-section of the following dimensions: 150×150, 100×100 i 50×50 mm. Frontal wall exposed to leaching process constituted salt face, whereas the other surfaces were coated with water-proof paint or were left in original state (Fig. 1).
The examinations were conducted in the devise described in details in the studies (Kamiński, Cyran 2014) and (Kamiński 2018). Mechanism of action of the device for salt rock leaching, as well as information about flow between individual components, is additionally shown in Fig. 2. Water flow forced by pump was marked with red colour. Temperature was controlled via heater installed in the container, whereas flow discharge was registered by suitable sensor. System for loading (pump with servomotor) and main chamber filled with salt and aggregate, are shown in the central part of the Figure 1. Data from individual module were registered in notebook via suitable connectors. Beside of data acquisition, also image recording with use of time-lapse camera, has been conducted.
Testing chamber was made of steel sheet S355 12 mm thick, and it was divided into opened and closed parts. Closed part of the testing chamber comprises tight system equipped with sleeve for hydraulic cylinder mounting. Hydraulic cylinder piston with pressing plate puts pressure on the salt sample. Load is transmitted via salt sample and aggregate onto testing plate, where stresses and deformations are generated. Suitable values are measured by extensometric converter and relocation transducer mounted at the measuring side of the testing chamber. Inflow and outflow valves allow control of the water flow direction and water discharge in the container. Overflow container having capacity of 70l allows water recirculation within the chamber – pumping unit – chamber system.

![Testing Chamber](image)

**Figure 3.** Model 3D of final version of the testing stand and photography of components before assembling

Pumping system comprises plastic filter, membrane pump of maximal discharge of 11,3 l/min, flow meter and set of valves: suction valve, inflow valve and outflow valve. Membrane pump construction guarantees safe operation in salt environment (internal part of the head is made of EPDM and santropen®, and the internal part – from polypropylene). Maximal pressure height up to 10 m. Depending on connection manner, pumping system allows flow from the top or from the side of testing chamber.

Hydraulic system comprises manual hydraulic pump (max 250 bar), hydraulic pipes, hydraulic cylinder and hydraulic fluid pressure sensor. The system was designed in such manner that for maximal operation pressure (180 bar) pressure of 80 kN was assured.

To realize the targeted examination, the testing stand had to be equipped with electromechanical accessories such as: pump and water heater. Application of additional electrical subsets was necessary to assure safety of the operator and testing stand devices.

### 2. Examinations

Conducted examinations were aimed at:

a) Confirmation that periodical leaching of salt rock sidewalls supported by coarse-grained aggregate stack is possible, and it allows effective controls (reduction) of the shaft lining load.

b) Preliminary recognition of the processes related with the salt rock walls leaching having influence on the offloading process dynamics by deformational pressures of the final shaft lining.
It was proved during the examinations that in result of dissolving process on the contact salt – aggregate, a salt bridge is formed (Fig. 4), which shape, dependently on the experiment characteristics, is similar to truncate cone or truncated pyramid. Individual tests were aimed at determination of the cone development mechanism and determination of its mine geometrical parameters.

Moreover, influence of the contact size, salt sample – aggregate, onto development of the salt tenon. Thus a trial of simulation of differential contact of the salt plane with single grain was undertaken.

In the next stage, on the basis of collected data, rate of frontal tenon development was modelled. The experiments were conducted with three different-sized samples. In the moment $T = 0$ the surface amounted for (100%), and then during washing process it was reduced until its destruction. Linear regression model of numerous variables was used in modelling, where explanatory variable was percentage of the surface occupied by salt tenon, and explanatory variables comprised: water temperature, water discharge per hour and time of the analysis. Square root of time was taken because it improved model tailoring and better described the examined phenomenon. The effect is visualized in graphical form in Fig. 5.
Salt rock wall dissolving model acting on some contact points where salt bridges are formed, has been developed in this manner.

The following empirical formulas shown below in descriptive and mathematical notation were obtained:

\[
\text{Percentage salt tenon surface} = (-0.0232 \cdot \sqrt{\text{time}} + 0.0376 \cdot \text{temperature} + 0.0456 \cdot \text{flow discharge})
\]

The Upper formula was tailored to measurements, thus in time \(T=0\), 100% is not always obtained. Such dependence talks rather about general tendencies with respect to temperature and flow discharge, and it indicates approximate time of the salt tenon of determined surface.

In result of this formula transformation, we can obtain time needed for leaching, in order to obtain critical surface \(A_{\text{critical}}\):

\[
\text{Time} = \left(\frac{0.0376 \cdot \text{Temperature} + 0.0456 \cdot \text{Flow discharge} - \text{percentage salt tenon surface}}{0.0232}\right)^2
\]

Where:

\[
\text{Percentage of salt tenon surface} = \frac{\text{Critical surface}}{\text{Salt wall surface}}
\]

We obtain final relation:

\[
P = \frac{\text{Salt tenon height}}{\text{Side wall advance rate}}
\]

Factor \(P\) informs about the time (in 24 hours) needed to create salt tenons of critical surface, which then would be destroyed with rate needed to be adapted to the side wall relocation. Leaching time is calculated from former equation.

On a basis of the developed salt tenon height, also block wall flushing rate was determined. Like in previous case, linear regression was applied. Salt rock leaching rate was assumed as constant and it was expressed as a ratio of the flushed salt height and its leaching time. Explanatory variables comprised flow discharge in litres per minute and temperature. It was observed that salt is also flushed out from the frontal tenon surface on the salt block contact with the obstacle. Height of the leached salt was determined for about of 20%. Data obtained in experiment are shown below.

In this manner an empirical formula for the salt wall leachin rate was combined with former formula for leaching time, what allowed determination of the dissolved salt \(H\) [mm]:

\[
H = V_{\text{leaching}} \cdot t
\]

Where:

\[
V_{\text{leaching}} = 0.66 \cdot t + 2.15 \cdot U + 89.42
\]

Fig. 6 illustrates the effects in graphical form.
Analysis of characteristic fragments within single sample

The first scenario of the analysis of obtained results comprised comparison of characteristic courses occurring within single test sample. Drop of the force from the same initial value lasting in determined time range in sequent simulation cycles of the rock body creeping, was examined.

- Analysis of test marked with symbol II.12

Information about experimental procedure:

a) Pressing force of the salt block to the shaft lining via cylinder.

b) Leaching during measuring works – Process the salt block washing with water in order to reduce the load.

c) Protected – salt block was covered with paint in order to allow dissolving of only one not protected wall – not protected wall having direct contact with shaft lining.

d) Only measurements lasting 600 s with initial value of the aggregate pile amounting for about 18 kN, have bee qualified for the analysis.

Using functionality of the application developed for needs of the analysis of drop of the force loading the leached element of the salt lump, individual fragments of the data were removed from the full set of results and then they were put on the diagram in order to compare the data. The result is shown in diagram presented in Fig. 7.
Figure 7. Comparison of individual loading cycles

Similar in subsequent leaching cycles inclination angles of the straight line approximating formation of the force loading the shaft lining in time can be observed in the diagram. Leaching rate expressed with tangent of the inclination angle of approximation line is slow, what results from the initial water salinity (result of the previous test), although continuous dissolving process and constant water temperature amounting for about 36 Celsius degree.

- Analysis of the test marked with symbol I.5

Information about experimental procedure:

a) Pressing force of the salt block to the shaft lining via cylinder.

b) Leaching during measuring works – process the salt block washing with water in order to reduce the load.

c) Protected – salt block was covered with paint in order to allow dissolving of only one not protected wall – not protected wall having direct contact with shaft lining.

d) Only measurements lasting 120 s with initial value of the aggregate pile amounting for about 30 kN have bee qualified for the analysis.

Like in previous case, fragments of the data were removed from full data set and then shown in one diagram for comparison purposes.
Figure 8. Comparison of subsequent loading cycles

Variable angle of line force approximation lines in time can be observed on the above diagram. Leaching rate is very high despite high salt brine salinity being result of conduction of previous tests. This high rate also results from salt sample protection on five sample sides in order to force leaching only fragment of plane being in contact with the lining.

It was also observed, that despite cyclic leaching process and keeping constant brine temperature amounting for about 38 Celsius degree C, the leaching rate was reduced in each sequent cycle.

- Analysis of test marked with symbol II.8

Information about experimental procedure:

a) Pressing force of the salt block to the shaft lining via cylinder.

b) Leaching during measuring works – Process the salt block washing with water in order to reduce the load.

c) Protected – salt block was covered with paint in order to allow dissolving of only one not protected wall – not protected wall having direct contact with shaft lining.

d) Only measurements lasting 375 s with initial value of the aggregate pile amounting for about 20 kN were qualified for the analysis.

In the diagram (Fig.9), variable angle of inclination of the approximation line changing in, time was observed. Leaching rate is low (tangent of the inclination angle) despite low level of the brine salinity – water was replaced before measurement.

It was also observed, that despite cyclic leaching process, the leaching rate is reduced in each sequent cycle (cycle 1, 2, 3) until the moment when all cycles have the same leaching rate (cycle 4, 5, 6) as it is influenced by increasing level of the leaching water, as well as low temperature of the leaching water (~20 Celsius degree).
Figure 9. Comparison of subsequent load cycles

Analysis of characteristic cycles from various tests

Next scenario of the analysis of obtained results comprises comparison of the characteristic fragment of the research process beginning. The analysis was aimed at the load drop in the first phase of relaxation, directly after the load application. The following samples were considered:

1) II.5 pressing force applied to plate, fresh stagnant water,
2) II.7 pressing force applied to cylinder, leaching with salted water,
3) II.8 Pressing force applied to cylinder, leaching with salted water,
4) II.9 Pressing force applied to cylinder, leaching with salted water.

Measurement fragments comprising the first load relaxation chase were qualified to the analysis, initial value within range 16 - 20 kN.

Test results from four measurements are shown in (Fig. 10). All samples comprised salt fragments from the same localization. Leaching water temperature was constant during all measurements and it amounted for 22 Celsius degree. It was observed on diagram related with test II.5 that small value of force (about. 16 kN) resulted with stoppage of water flow and camping force, caused development of large number of salt tenons and caused (threefold) elongation of the load relaxation time. Thus we can conclude that clamping force of the salt rock (directly and tightly) inserted to the shaft lining may cause retardation of the leaching process. Results of testing of other samples confirm rightness of the application of aggregate used as intermediate layer between the shaft lining and salt rock body.

Next tests II.7 and II.8 are similar. However greater process rate was observed in the first case, where relaxation has similar rate despite the fact that in test II.7 water was replaced with fresh water. Thus we can conclude, that water salinity has no considerable influence onto leaching rate.
In the test II.9, elongation of the time of the first relaxation, was observed. It resulted from increase of the water salinity during conducting the tests II.7 and II.8. In case of the test II.9, leaching time was elongated, despite of active water circulation.

Next analysed phenomenon was related with destruction of the salt tenons in subsequent cycles of the rock body relocation.

Fragments illustrating process of the salt tenons destruction are shown in (Fig. 11 and Fig. 12). Fragments of testing results, in which load causing rock body relocation after leaching process, have been selected from measurement data. Curve 1 illustrates course of the first cycle of sample loading, observed fluctuations result from sample settlement in the test stand. Curves – 2, 3, 4 and 5 (in case of tests II.8 and II.9) comprise data fragments from subsequent relaxation processes, in which destructive processes were observed.

**Figure 10.** Comparison of individual loading cycles
Figure 11. Comparison Courses of the salt tenon destruction in test II.8 of individual loading cycles

Figure 12. Courses of the salt tenon destruction in test II.9
Phenomenon of the salt tenon levelling can be observed in the diagram, in which force course data were replaced with their derivative. Local maxima and minima reflect dynamic changes occurring in the time when the rock body press onto shaft lining and salt tenons developed during leaching process are not able to bear compressive force and they are exposed to dynamic destruction. Maxima/minima of the beginning and the end of measurement range result from errors of the numerical differentiation.

3. Conclusions

Problem of the mine working stability in salt rock body is not new. The problem was discussed in thousands of research studies and publications.

Perspective of further development of copper mining within Pre-Sudethian Monoclyne, as well as, advance of exploitation front in northern direction will be related with necessity of making some development headings in the salt rock body. These headings, as long lasting headings, must guarantee rock body stability for the decades. Shafts with lifts mast also guarantee permanency of the shaft reinforcing geometry allowing high speed of the shaft lifts movement. Before starting works related with salt formations, we should realize that problems of salt rock geo-mechanics are very complicated and different for individual rocks. Each examined case should be based on parameters prescribed to given beds.

Analysis of literature and available data from research works allowed the following conclusions:

a. Shafts built for needs of KGHM Polska Miedź will penetrate salt rock body on sections of different length on the depth about 1000 m.

b. The shafts in question will be exposed to high rate convergence of relatively high rate and relatively big relocation of the shaft sidewalls. After 4 years of sinking of the shaft SW-4, convergence of the shaft sidewalls proved in situ amounts for about 0,5 mm/24 hours, so yearly dislocation of the shaft sidewall amounts for about 18 cm.

c. Yielding lining used in the shaft SW-4 can be used only because of the fact that the shaft has no lift and gradual dislocations of the shaft sidewalls play no considerable role, despite decrease of active ventilation cross section.

d. Temporary rebuilding of the shaft within the salt section is coast-bearing, and the normal shaft operations must be stopped what will generate very high cost, as was described in chapter 8, and it will be technically very complicated process.

e. Application of similar solution of the shaft lining will not be possible because precise operation of the shaft lifting bucket, both in case of rigid reinforcement, and in case of rope system.

Described in the present study procedure of the control of shaft lining load via suitable construction and suitable operations procedure takes advantage from common defect of the salt rock body. i.e. its high solubility of fresh water. In this case, this rock property is considered as its great advantage.

Preliminary examinations conducted and documented in the present study proved that process of controlled leaching of the salt sidewalls of shaft opening is possible. Application of this process in practice should be a new tool used for elimination of the deformation pressure inserted onto shaft lining.
Designed device for salt rock leaching allowed obtaining answer for only basal questions related with described problem, whereas solutions for numerous technological questions require application of large-scale models in situ.

The solution of such complex problem proposed in the present study requires conduction of further examinations related both with leached salt properties and forecasting and measuring rates of salt rock body creeping into the shaft, as well as its effective and uniform leaching.

It should be underlined that results of the executed examinations indicate that after temporal leaching, grained filling of the contact layer can and should be voided from fluid (and brine). Thanks to that the shaft tubing lining will not be additionally loaded with hydrostatic pressure coming from the brine having definite aggression to construction materials.

Application of new construction solutions allows evident elimination of planned rebuilding works i.e. operation downtimes of the shaft work, what is very important in case of production shaft.

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