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AN INNOVATIVE SOLUTION TO COUNTERACT CONVERGENCE OF SHAFT LINING IN ROCK SALT STRATA

KONWERGENCJA OCIOSÓW SZYBÓW W GÓROTWORZE SOLNYM – INNOWACYJNA METODA PRZECIWDZIAŁANIA

This work presents an innovative shaft-lining solution which, in accordance with a patent of the Republic of Poland, allows successive, periodic leaching of excess rock salt migrating to the shaft opening. As is commonly known, all workings in rock salt strata are exposed to an increased convergence of sidewalls, making it very difficult to use shafts properly. Rocks migrating towards the shaft opening cause very high stress on the shaft liner. As a result, if the lining does not show substantial deformability, it fails. Lining failure due to insufficient deformability has been extensively described in the literature. Also, throughout the history of mining construction, a number of solutions have been proposed for different types of lining-deformability enhancement. For instance, the KGHM mining corporation applied a deformable steel lining – a solution used in the mining construction of galleries – along a 155-m-long section of the SW-4 shaft with diameters of 7,5 m that passes through a rock salt strata. At KGHM, the SW-4 shaft passes through a rock salt strata along a section of 155 m, in which a deformable enclosed steel lining was made. After several years, the convergence of shaft sidewalls stabilised at a rate of 0.5 mm/day. This enormous activity of the rock mass made it necessary to reconstruct the entire shaft section after only four years. According to further predictions, it will be necessary to reconstruct this section at least four times by 2045. This paper discusses in short form the underlying weaknesses of the technology in question.

As a solution to the problems mentioned above, the authors of this work present a very simple design of a shaft lining, called the *tubing-aggregate lining*, which utilises the leachability of salt rock massifs. The essential part of the lining is a layer of coarse aggregate set between the salt rock sidewall and the inner column of the tubing lining. One the one hand, coarse aggregate supports the salt rock sidewall and is highly deformable due to its compressibility, but on the other hand it allows water or low saturated brine to migrate and dissolve salt rock sidewalls.

This paper presents the first stage of works on this subject. Patent No. PL 223831 B had been granted before these works commenced.

Keywords: shaft lining, convergence of workings, rock salt strata, rock salt formation, geomechanics

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Praca niniejsza prezentuje innowacyjne rozwiązanie obudowy szybu, która zgodnie z patentem RP umożliwia sukcesywne okresowe ługowanie nadmiaru soli migrującej w światło szybu. Powszechnie wiadomo, że każde wyrobisko górnicze w górotworze solnym narażone jest na zwiększoną konwergencję ociosów, co w przypadku szybów jest dużym utrudnieniem prawidłowego ich wykorzystywania. Migracja skał w światło szybu powoduję bardzo wysokie obciążenie deformacyjne obudowy. Jeżeli ta nie ma zdolności do znaczącego odkształcania się to ulega zniszczeniu. Literatura fachowa dysponuje wieloma opisami zniszczenia obudowy zbyt mało podatnej. W historii budownictwa górniczego zaproponowano też kilka rozwiązań w postaci różnego rodzaju upodatnienia obudowy. Przykładowo, przenosząc z budownictwa górniczego wyrobisk korytarzowych konstrukcję obudowy stalowej podatnej w KGHM w szybie SW-4 na odcinku o długości 155 m, przechodzącym przez górotwór solny, zastosowano podatną obudowę stalową zamkniętą. Konwergencja ociosów szybowych w tym przypadku po kilku latach ustabilizowała się na poziomie 0,5 mm/dobę. Efektem tak wielkiej aktywności górotworu była konieczność przebudowy całego odcinka szybu już po 3 latach. Dalsze prognozy przewidują, że do roku 2045 konieczna będzie jeszcze co najmniej 4 krotna przebudowa tego odcinka. W pracy przedstawiono zasadnicze słabości tego rozwiązania technicznego.

W odpowiedzi na tego typu przypadki Autorzy niniejszej pracy prezentują bardzo prostą konstrukcje obudowy zwanej obudową „tubingowo-kruszywową”, która wykorzystuje zdolność górotworu solnego do procesu ługowania. Istotą tej obudowy jest warstwa kruszywa gruboziarnistego, umieszczona pomiędzy ociosem solnym i wewnętrzna kolumną obudowy tubingowej. Kruszywo gruboziarniste z jednej strony podpiera ocios solny z możliwością znacznego odkształcania się bo jest ściśliwe, ale z drugiej strony pozwala na migrację wody słodkiej, która będzie oddziaływać na ociosy solne rozpuszczając je.

Niniejsza praca poprzedzona przyznanym patentem nr PL 223831 B, prezentuje pierwszy etap prac nad tym zagadnieniem. Etapem drugim były badania intensywności ługowania i możliwości zastosowania tego rozwiązania w budownictwie szybowym. Etapem finalnym winien być odcinek badawczy szybu w górotworze solnym z obudową pozwalającą na okresowe ługowanie calizny solnej.

Słowa kluczowe: obudowa szybów, konwergencja wyrobisk, górotwór solny geomechanika górotworu solnego

1. Introduction

Salt rock is one of the key minerals forming the crust of the Earth, and rock salt is a very important raw material for industrial applications. A total of 276.7 million tons of rock salt were extracted in 2016 (Reichl at al., 2018) for use in the food and chemical industries, as a road defrosting agent and as a coolant for artificial ground freezing in underground construction.

Salt rocks exhibit a very important geomechanical parameter of high creep compliance when exposed to long-term loading. Rock salt also has a number of other unique properties, such as complete non-permeability for both gases and water. This property makes it possible to create cavities in salt deposits which can be used to store gas or liquid hydrocarbon, as well as noxious waste, including spent nuclear fuel from nuclear plants.

Salt rocks also have a high solubility in water. This property is used in the process called “leaching”, which is employed for solution salt mining, but also to form cylindrical cavities used for underground storage areas.

However, the strong rheological properties of salt make it very difficult to maintain workings in salt rock mass while ensuring that their size does not change. For instance, ample evidence exists that shaft linings in salt rock mass tend to fail after a certain time, with shafts converging consistently as a result of radial displacements of the salt rock body towards the interior of the shaft.

In these circumstances, special technological measures must be taken in shafts in salt rocks to neutralise the effects of excessive convergence of salt rock sidewalls.

2. Convergence in salt rock workings

A considerable body of international research and literature exists on the atypical – as compared to other rocks – load behaviour of salt rocks.

The extensive literature analysed, *inter alia*, in the doctoral dissertation by Maj (Maj, 2009), suggests that the convergence of salt rock sidewalls in salt rock strata depends on multiple factors, such as salt type (different in each Polish salt deposit), depth of the workings, lifetime of mining operations, in situ temperature, etc.

Studies by Bieniasz & Wojnar (1995 & 2007) suggest that convergence in typical horizontal excavations with a width of 5-7 m and height of about 4 (Bieniasz et al., 2011): varies considerably between individual salt deposits (Fig. 1). For instance, the relative convergence observed in the Wieliczka Salt Mine is currently close to zero, while the Sieroszowice salt deposit has experienced convergence ranging from 40 ‰/year at the early stage of the workings to 10 ‰/year after several years of mining operations (Maj, 2009).

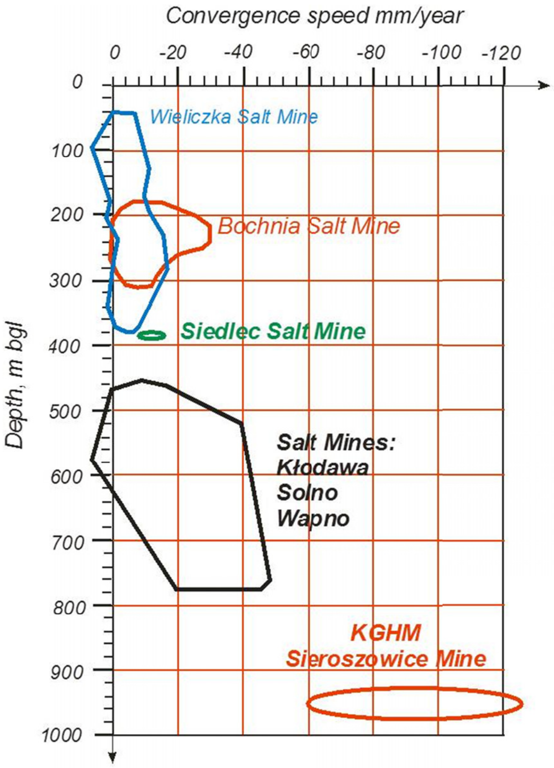

Fig. 1. Relationship between the rate of convergence and the type and depth of salt deposits (based on Bieniasz & Wojnar, 2007, 2011)

Difference in the course of convergence in excavation in Polish salt deposit can be presented on an example (Kamiński, 2018), among other works on this subject, provides only examples of the real creep values for salt rock sidewalls, measured in specific locations of Polish salt deposits, including:

- sidewall convergence in the Campi shaft in the Bochnia Salt Mine;
- salt rock sidewall convergence in the cavities of the Kłodawa Salt Mine;
- convergence in the cavities of the Sieroszowice salt deposit;
- sidewall convergence in the SW-4 shaft, the Sieroszowice Mine.

2.1. Sidewall convergence at the Campi shaft in the Bochnia Salt Mine

Theoretical and experimental works by Kortas (Kortas 2004, 2010b) provide a very clear description of the mechanism in which loads on the shaft lining increase over time. This phenomenon can be illustrated by the two failures of the rigid, concrete lining of the Campi shaft, in the Bochnia Salt Mine, where convergence exceeded 4.0 ‰/year (cf. Fig. 2), causing radial displacement of the salt rock towards the interior of the shaft. After the first failure, the shaft was reconstructed and provided with a new concrete lining.

After a certain period, however, convergence led to the cracking of this new lining as well.

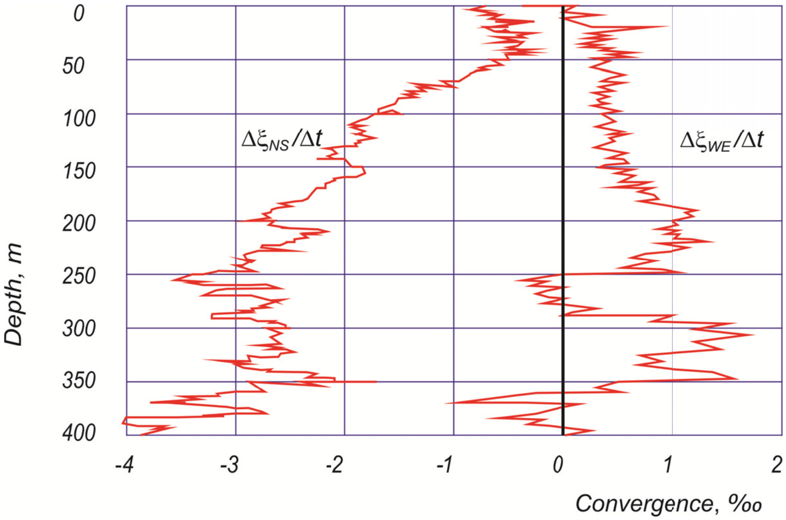

Fig. 2. Convergence observed for two perpendicular directions in the Campi shaft of the Bochnia Salt Mine (based on Kortas, 2004)

Symbols: $\Delta\xi$ – sidewall contour displacement increment, Δt – time increment

Fig. 2 shows a variable convergence of shaft sidewalls, measured for two azimuths perpendicular to each other, indicating anisotropy, which is another notable salt rock property found in this deposit. The rigid, concrete lining of this shaft has failed despite the convergence being relatively weak compared to other salt deposits (cf. Fig. 1). This clearly suggests that the only way to secure the lining against failure, or to delay its failure, is by enhancing the deformability of the rigid lining to to delay application of the load on the lining.

2.2. Salt rock sidewall convergence in the cavities of the Kłodawa Salt Mine

In qualitative terms, Jankowska and Kwaśniak (2015) obtained similar results by taking long-term measurements of sidewall convergence in the salt rock galleries of the Kłodawa Mine, Zone 2, Vertical Measuring Line Points No. 0 and 21, located on two extraction levels: 525 m and 600 m.

The results of these studies prove that the convergence of sidewalls of salt rock workings depends on multiple factors, which is why the measurement technology and instruments are of great importance. Jankowska and Kwaśniak (2015), both land surveyors, describe the basic measurement methods and equipment for long-term recordings of sidewall displacements in salt-rock workings.

For practical purposes, a general relationship was derived for this type of salt to describe the so-called model convergence curve with the following equation (Jankowska & Kwaśniak, 2015):

$$f(t) = e^{-\alpha t + \beta} + \delta \tag{1}$$

where:

f — working-contour convergence,
t — time parameter,
$\alpha, \beta,$ — parameters describing the shape of the approximation function,
δ — model-translation parameter.

Over a period of 30 years, the sidewalls of the workings showed a displacement as high as 350 mm. Notably, this deposit exhibits much lower rheological activity than the Sieroszowice deposit (cf. Fig. 1). Example results from the work by Jankowska & Kwaśniak (2015) are provided in Figure 3.

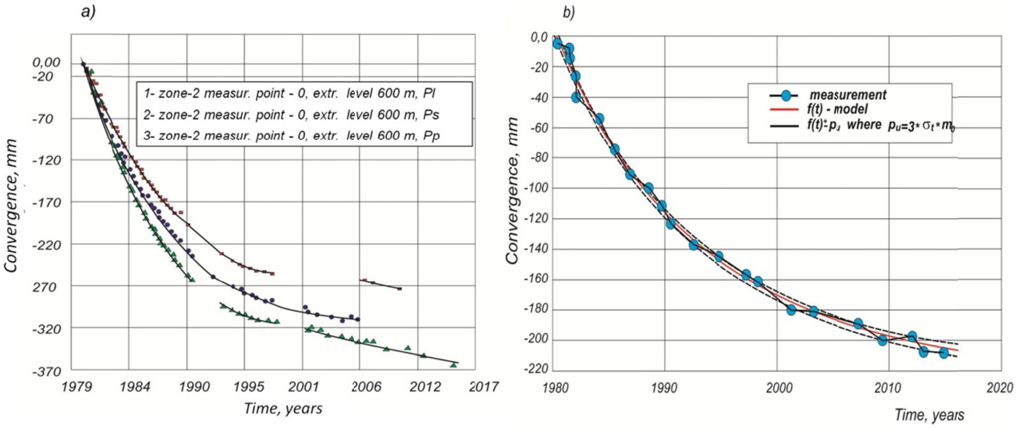

Fig. 3. Results of a long-term observation of salt rock sidewalls in the workings of the Kłodawa Salt Mine (based on Jankowska, Kwaśniak, 2015)
a) Measurement results, b) Shape of the example model function described by the equation (1)

These results provide a clear picture of how the convergence process progresses in the long term. Over a period of several decades, the sidewalls of the workings in the rock salt strataspecific to the Kłodawa Salt Mine have moved towards the interior of the workings by as many as dozens of centimetres, with the rate of this displacement decreasing over time.

2.3. Convergence in the cavities of the Sieroszowice Mine salt deposit

Salt rocks from the Fore-Sudetic Monocline (the Sieroszowice Mine and Głogów Głęboki area) have been a subject of interest because of the need for exposing this region's further copper ore deposits for extraction. Located at a depth of more than 1,000 m, this deposit lies under a salt rock layer, within a distance of several dozens to 200 metres. On the axis of the SW-4 shaft, the thickness of salt rock formations reaches 155 m, which means that maintaining the shaft along such a long section poses a considerable technological challenge.

Convergence measurements in the Sieroszowice-Polkowice Mines began between 1991 and 1997 during the mining explorations of the salt deposit (Bieniasz et al., 2011). Three measurement stations were installed in drifts with a width of 5-7 m and height of about 4 m, located at a depth greater than 900 m below ground level, to observe drift deformations. Observations began two weeks after the drifts were made to capture the phase in which the salt rock bodies were moving at the highest rate (Bieniasz & Wojnar, 1995; 2007). In the first phase of intensive convergence, which lasted a year, the convergence rate reached 250 mm/year (Fig. 3). In the following years, the convergence rate decreased and stabilised gradually, ranging from 40 to 70 mm/year in the sixth year of the study (Bieniasz & Wojnar, 2007).

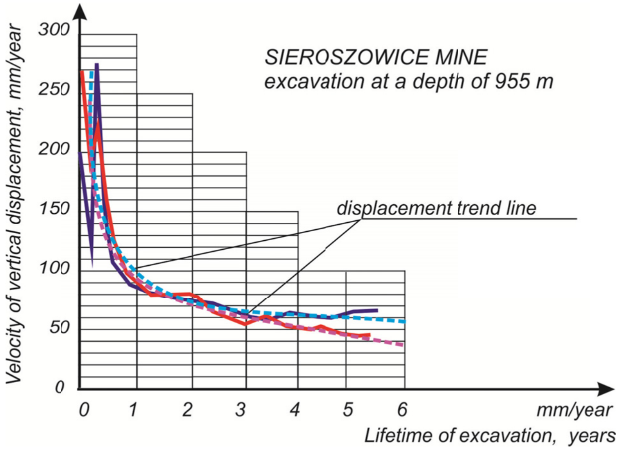

Fig. 4. Speed of convergence in the oldest-salt deposit in the Sieroszowice Mine (based on: Bieniasz & Wojnar, 2007)

Convergence measurements were resumed in one of the three stations in 2009. In 2010 this station recorded convergence ranging from 25 to 30 mm/year. Also, further measurement stations were added at a depth of 894 to 952 below ground level, in drifts and cavities with a cross-sectional area of 13 to 187 m^2 (Bieniasz et al., 2011). The above-described pattern of working deformation is typical for salt deposits, where a phase of intensive displacements at the early stage of the working is followed by several years during which the convergence rate is decreasing, and then by a long period of slow convergence at a constant rate (Bieniasz et al., 2011).

2.4. Sidewall convergence in the SW-4 shaft in the Sieroszowice Mine

In order for the copper mining industry within this area to develop in the future, new shafts must be constructed. These shafts pass through salt rock formations at a depth of about 1,000 m. This requires the shaft lining to remain stable despite the very high deformation pressures occurring at this depth.

Given the conditions of the Legnica-Głogów Copper District, assuming, based on the chart (Fig. 1), that the lowest-possible creep of the shaft-opening contour with a diameter of 10 m (in the opening) is 10 ‰/year, one can expect the shaft's diameter to decrease at a rate of about 100 mm a year. The extensive studies conducted at the CHEMKOP Research & Development Centre in Kraków were augmented by a number of highly valuable analyses performed at the SW-4 shaft (diameter inside lining is 7.5 m) built for KGHM mining corporation between 2008 and 2014.

Based on studies and observations conducted in this shaft, the researchers verified the actual scale of shaft sidewall creeping (Fabich et al., 2016). Between 2013 and 2014, convergence measurements were taken at eight stations of the salt rock section of the SW-4 shaft. This section was being lined as the shaft sinking progressed. Located at the shallowest depth of 1,066.2 m, the first station could be used for measurements for 495 days, whereas the eight and deepest point, at 1,159.6 m, provided results for 303 days.

Based on these measurements, a curve was produced to show convergence trends over time, providing insights that would be very useful for the projection of shaft-sidewall convergence and the design of shaft linings. Fig. 5 shows the rock salt creep trend and the table and chart in Fig. 6 demonstrate the qualitative changes registered by the eight measurement stations.

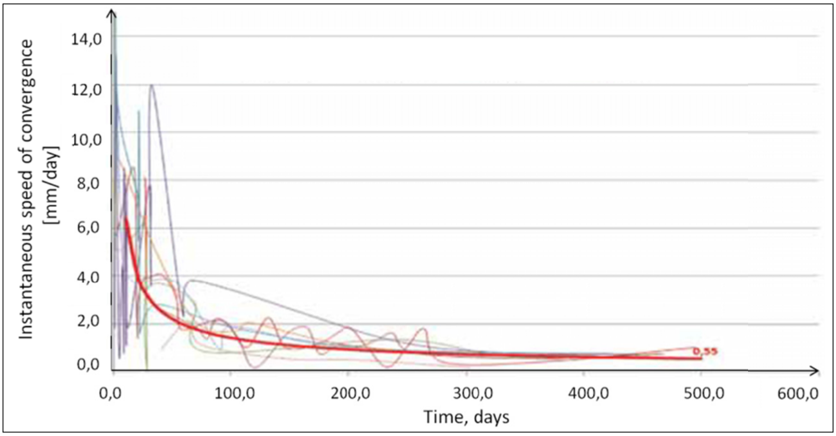

Fig. 5. Shaft sidewall convergence trend in the SW-4 shaft between 01 February 2013 and 11 June 2014 (Fabich et al., 2016)

Stand number	Depth	Time	Diameter	Reduction in diameter	Average convergence
	m	days	m	m	mm/day
1	1060,2	495	9,2	0,8	1,62
2	1084,6	468	9,36	0,64	1,37
3	1099,6	456	9,34	0,66	1,45
4	1114,6	447	9,3	0,7	1,57
5	1124,6	423	9,37	0,63	1,49
6	1129,6	410	9,42	0,58	1,41
7	1144,6	393	9,52	0,48	1,22
8	1159,6	303	9,81	0,19	0,63
	Average convergence, mm/day				1,34

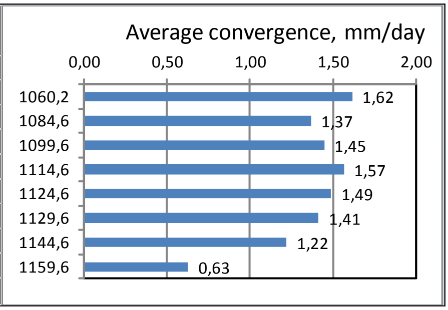

Fig. 6. Average annual convergence causing a decrease in the SW-4 shaft's diameter (based on Fabich et al., 2016)

An average shaft sidewall convergence of 1.34 mm/day means that the annual convergence of the sidewalls of a shaft with the opening diameter of 10 m will decrease by about 49 cm a year.

Already in 2015, this highly intensive sidewall movement in the SW-4 shaft made it necessary to completely reconstruct the shaft's lining along the section passing through salt rock formations. The reconstruction involved the dismantling of the old steel arch lining and construction of a new one. No changes were made in the design and construction method of this new lining. However, the designers expected that further reconstructions would be necessary about every 12 years.

3. Design solutions to secure shafts in salt rock massifs against excessive convergence

3.1. Mining shafts in salt rock layer

In various parts of the world, extensive research has been conducted on salt rock behaviour. In part, this has been due to the construction of underground hydrocarbon and noxious-waste storage areas in salt rock formations. The research has yielded a multitude of solutions which should be considered in the design and construction of mine shafts passing through salt rock formations, including the shafts constructed for KGHM.

Due to the geomechanical properties of salt rock mass and their substantial creep compliance, shafts – as long-term workings – are exposed to increased deformation loads causing the load bearing capacity of the lining to be exceeded. Deformations of different types of salt rocks vary considerably as a function of time. Example patterns of this relationship, approximated by the general power function (Kortas, 2010a):

$$\varepsilon(t) = \varepsilon_0 + at^c \tag{2}$$

are presented for several types of salt rocks in Figure 7 (Kortas, 2010a).

As mentioned in the summary of Chapter 2, this high rate of salt rock sidewall creep in the shaft cannot be stopped by traditional shaft linigs, and no solution has yet been developed for such enhancement of lining deformability that would ensure long-term interaction with the salt

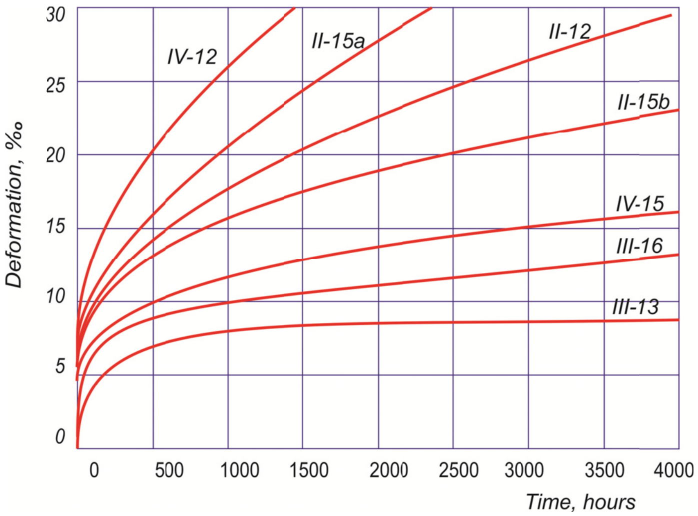

Fig. 7. Example results of creep tests involving different types of salt rocks approximated by the power function of time (based on Kortas, 2010a)

rock massif. Thus, it is necessary to look for new solutions for seamless shaft mining in salt rock massifs. Below, we provide a brief discussion of the existing technological solutions that have been proposed for shafts in salt rock massifs.

3.2. Enhancing shaft-lining deformability with a layer of compressible material

Polish Patent PL 105345 describes a lining useful for shafts passing through layers of salt rocks that are prone to radial creep. The lining comprises the outer layer made of granulated material with good crushing strength and the inner layer made as a wall from bricks, bentonite and concrete. The thickness of the outer layer is a function of the rate at which the rocks move towards the shaft, while the thickness of the inner layer depends on the shaft's technological conditions and purpose. The outer layer can carry the loads directed towards the inner layer, thereby preventing the shaft's diameter from decreasing. Consequently, even if such a deformation does occur after a certain time, the reconstruction of the lining is fairly simple.

3.3. Enhancing shaft deformability using perforated ceramic elements

Polish Patent PL 140894 presents a shaft-lining solution in which the rock-mass side of the lining features a deformability-enhancement layer made of perforated ceramic elements or other high-compressibility construction materials, with the load bearing capacity of this layer depending on the degree of deformation and destressing of the surrounding rocks. The boundary value of this lining's load bearing capacity should be lower than the bearing capacity defined for the design strength of the preliminary or final lining.

3.4. Hydraulic lining

Another potential solution, provided by Chudek et al. (2009), involves a hydraulic lining, where a cylindrical brine tank is constructed behind a water-proof inner lining to support the shaft sidewalls through hydrostatic pressure. This solution could be applied for rock salt strata layers with a low thickness. For a very thick salt rock mass, it would be necessary to maintain a sufficiently high brine column to generate a very high hydrostatic pressure in the lower part of the column. In these circumstances, the inner ring of the water-proof lining would also need to have a very high load bearing capacity and very low permeability. In practice, however, this solution would be difficult to implement.

3.5. Deformable steel lining in the SW-4 shaft

The measurements involving SW-4 shaft sidewalls, as presented in Chapter 2.4, yielded exceptionally high convergence values. At 1.34 mm/day (490 mm/year), the annual average convergence recorded during these measurements made it necessary to apply a lining with good deformability. To respond to this problem, a solution designed by KGHM Cuprum (Fabich et al., 2016) was applied in the SW-4 shaft, involving a circular arch enclosed lining made of a rolled V25 section, with an inner bend radius of 4,875 mm. According to Fabich (2016), a single ring of the lining comprises 10 elements linked by two-legged stirrups. Vertically, the rings are separated by pipe struts. The lining's arches are anchored to the rock salt strata using KE3-2K drop-in anchors with a 2.5-m-long APG rod and a protection mesh made of wires measuring 0.8 mm in diameter, with a mesh size of 12.7×12.7 mm, fastened to vertical-strut bolt brackets.

Due to the very high rate of salt-mass movement, the entire 155-m-long section of the shaft required reconstruction after only four years. The purpose of the reconstruction undertaken in 2015 was to remove the excess rock that had moved towards the shaft opening as a result of

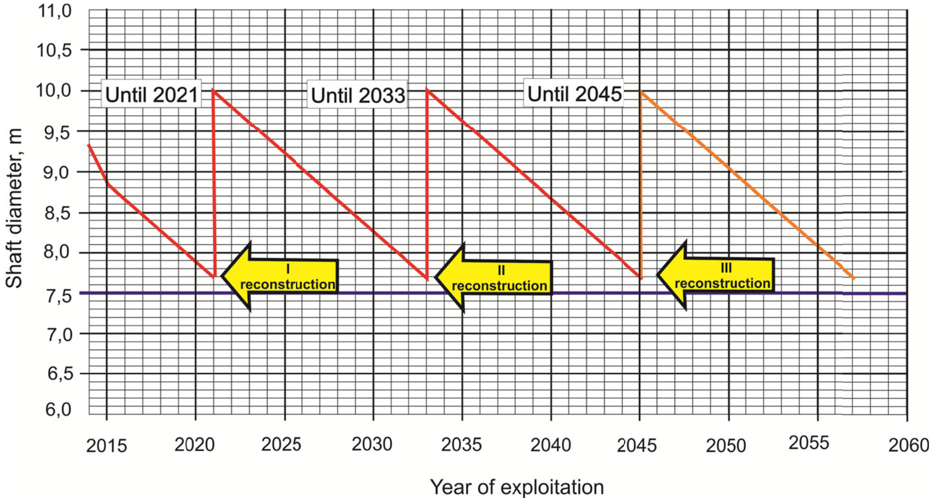

Fig. 8. Hypothetical plan for SW-4 shaft reconstructions along the salt rock section (based on Fabich et al., 2016)

permanent creep. To this end, the lining was dismantled, and the salt rock layer was broken up to achieve the desired opening diameter of the shaft.

In 2017 the creep process stabilised at 0.5 mm/day, meaning that it is still at around 18 cm a year. Consequently, further reconstructions are inevitable. According to the projections made by Fabich et al. (2016), the shaft will have to be reconstructed at least three more times in order to ensure its stability until 2045. This line of thinking assumes that the diameter of the SW-4 shaft might decrease within the lining to 7.5 m. Apart from the fact that it is impossible for the lining of this structure to undergo such deformation without damaging the stirrups that link the anchors, the cost of such an operation and the need to alter the shaft structure should be considered as valid concerns. Based on Fabich (2016), Figure 8 presents the projected reconstruction schedule for the salt rock section of the SW-4 shaft until the year 2045.

3.6. Weaknesses of the deformable enclosed circular steel lining in the SW-4 shaft

Such substantial deformations in the workings of the SW-4 shaft along the salt rock section required the use of a highly deformable lining. Based on this insight, the designers concluded – incorrectly, in our opinion – that a deformable steel arch lining would have the desired properties. Accordingly, the mining company applied circular rings consisting of rolled V25 sections (as per PN-G-15000-02:1993, PN-G-15000- 03:1993, PN-H-93441-3:2004 standards), spaced every 0.75 m, with an inner bend radius of 4,875 mm.

A single ring of the deformable circular lining, adapted to the nominal diameter of the opening diameter of 10+0.08-0.02 m, comprised 10 arches made of V25 sections linked by two-legged stirrups.

The most important disadvantage and obstacle in the proper work of the shaft lining constructed in this way is the changing arch curvature as a result of convergence. In differential geometry, the curvature of the flat curve is expressed by the degree of its deviation from the static straight line at the analysed point. For instance, a circle with the radius r has a constant curvature equal to $k = 1/r$ at all its points.

Since the lining's arches are bent for a curvature corresponding to the shaft radius in the opening, equal to 4.875 m (the curvature $k = 1/ 4.875 = 0.205$), it takes a diameter decrease of only 1.0 m (Fig. 9) for the curvature to increase to $k = 1/4.5 = 0.222$). If the ring construction required the use of 10 elements, then each element's length will be $l_1 = 3.14$ m without overlaps, and with 0.5-m overlaps, the length will be $l_2 = 3.64$ m. A decrease in the ring radius from $r_1 = 4.875$ to $r_2 = 4{,}5$, i.e. by 0.375, causes a change in the curvature, as a result of which the arches do not adhere to each other as in their original state, generating very high tensile stress in the stirrups that link them. The underlying mechanism is illustrated in Figure 9.

Simple calculations indicate that a change in the ring's diameter by 1.0 m (from 10.0 to 9.0 m) causes the circumference of a single arch to shorten by the length Dl:

$$\Delta l = p(d_1 - d_2)/10 = 3.14\ (5 - 4)/10 = 0.314 \text{ m}$$

Accordingly, the length of an arch overlap increases from 0.5 m to 0.814 m. Such a decrease in the shaft's diameter produced by sidewall convergence is already enough to cause the stirrups to break as a result of a 0.814-m lever, leading the affected ring of the deformable lining to lose its load bearing capacity.

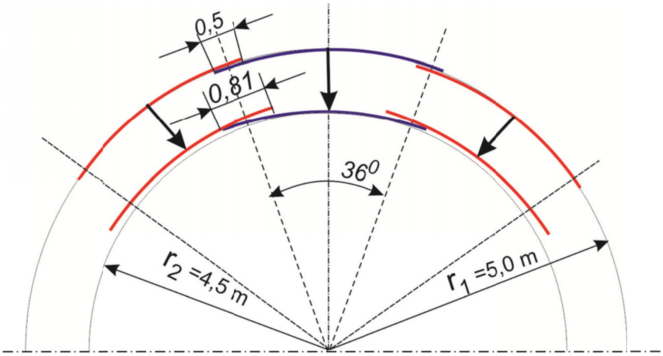

Fig. 9. Mechanism illustrating the formation of stress on stirrups in an steel arch lining of the SW-4 shaft (author's work)

This made it necessary to reconstruct the SW-4 shaft along the salt rock layer section. With the salt rock moving at a stable rate of about 0.2 mm/day, further reconstruction plans will have to be devised for this section.

Each reconstruction of the SW-4 shaft's lining along the entire salt rock section (155 m) is a project that:

- involves substantial expenditures;
- disrupts the operation of the shaft for a long period of time;
- does not guarantee that the shaft will remain stable in the long-term.

According to Fabich et al. (2016), if the shaft sidewalls continue to creep at the existing rate, the salt rock section of the shaft will have to be reconstructed every 12 years, a period in which the shaft's diameter can decrease to its minimum – that is, to 7.5 m in the lining' opening. The expected hypothetical rate of shaft sidewall convergence and the planned reconstruction schedule for the SW-4 shaft's lining until 2045 is presented in Fig. 8.

3.7. Summary of Chapter 3

The shaft-lining solutions presented in Chapter 3 involve the construction of a compressible layer around the shaft's lining. Compressed by the load of the rock mass, the layer protects the final lining from the direct impact of the rock mass. However, when the shaft passes through rock salt layers with rheological properties, it should be expected that after a certain period of deformable-layer compression, the core lining will be exposed to substantial loads, potentially leading to its failure. In such conditions, even a tubing lining that exhibits the highest compression strength might fail to provide complete protection against deformations and failure.

4. New design concept for a shaft lining sunk in salt rock formations

This Chapter will propose a solution involving an innovative lining with a working name of **tubing-aggregate lining**, as given by Kamiński (Kamiński, 2018). This lining uses the disadvantageous property of rock salt massifs of being leachable by water or low saturated brine. Accordingly, instead of dismantling the lining and mechanically removing the excess salt rock that has moved towards the interior of the shaft, it is enough to expose salt rock sidewalls to water or low saturated brine for a certain period of time to dissolve excess salt, thus neutralising the creep effect. In order for this process to be possible, a chamber must be created between the salt rock sidewall and the shaft lining to allow water or or low saturated brine to migrate. However, this chamber may not be empty because the inner column of the lining must stay in contact with the rock mass. In this solution, sidewalls will be supported by coarse-grained aggregate mixture, providing the additional benefit of allowing water to flow freely through the intergranular cavities, and to dissolve salt rocks.

The underlying mechanism of how the innovative tubing-aggregate lining works is shown in Fig. 10.

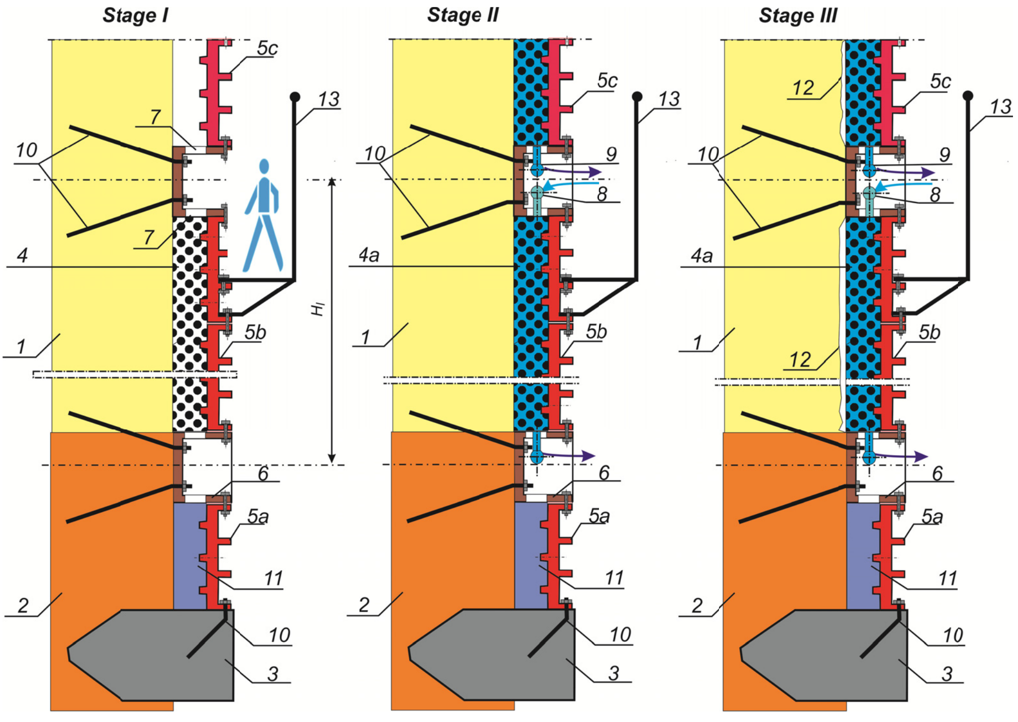

Fig. 10. Authors' concept of a tubing-aggregate lining for a salt rock section of a shaft (according to the patent: Czaja, Kamiński, 2016).

Stage I. Mmounting the shaft lining from bottom to top, **Stage II** – periodical leaching with a ordinary watter or low saturated brine. **Stage III** – results of periodical leaching (chamber 12)

Where: 1 – rock salt, 2 – strong rock layers, 3 – basic lower curbs, 4 – contact layer of aggregate, 4a – contact layer of aggregate fulfil with brines, 5,5, 5b, 5c – inner column of tubing lining, 6 – sealing and stabilization of technological ring, 7 – control and technological hole 7 –anchors fastening the technological ring, 8 – firm rock mass over salt layers,8, 9 – pipelines and hydraulic installation, 10 – anchors fastening the technological ring, 11 – concrete shaft lining, 12 – salt rock being leached, 13 –service platform

Similarly, Figures 11 and 12 provide an illustration of the design of the tubing lining's load bearing column.

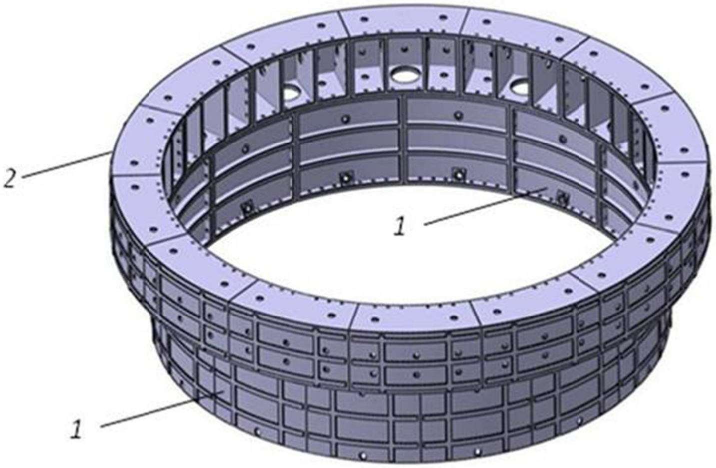

Fig. 11. Illustration of the tubing lining's load bearing column.
Symbols: 1 – Standard tubings, 2 – Tubings for construction rings

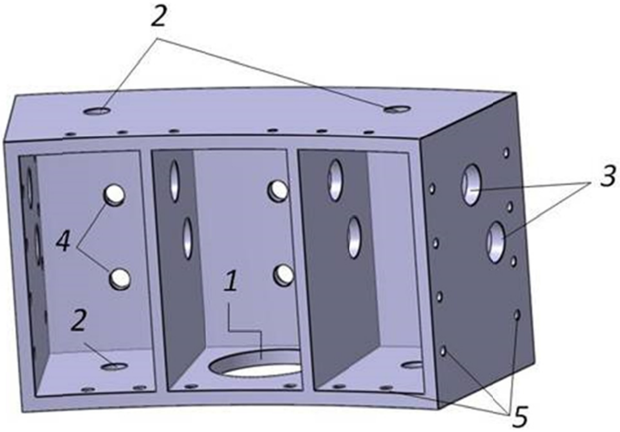

Fig. 12. Design of construction-ring tubing.
Symbols: 1 – inspection holes with a diameter of at least 300 mm to view the aggregate (leach) chamber, 2 – plumbing holes, 3 – holes for collectors to feed and gather the leachate, 4 – holes for anchoring rings in the rock mass, 5 – holes for tube connection

According to Polish Patent PL 223831 B1 (Czaja & Kamiński, 2016), the structure of a tubing-aggregate lining comprises the following (cf. Fig. 10):

a) Internal tubing column (5) constructed upwards and supported by a base ring beam (3) incorporated into the rock mass (2) that is deposited directly beneath the salt rock layer (1). The tubing column is assembled from standard tubings commonly used in contemporary shaft construction.

b) Special construction rings made of tubings (6) shaped similarly to standard tubings (cf. Fig. 11 and 12), anchored (10) in the rock salt strata(1) (Fig.10). The construction rings divide the salt rock section of the shaft into shorter sections with the length H_l, to brace the whole column and reduce hydrostatic pressure in individual sections.
c) Access walkways (13), permanently incorporated into the tubing lining so that the leaching of individual rock salt strata sections can be monitored.
d) Aggregate chamber serving as a leaching chamber, located between the sidewall (1) and the column of the tubing lining (5a, 5b, 5c) filled with coarse-grained aggregate (4) with high mechanical durability – (preferably magmatic aggregate) – whose cavities facilitate the flow of partially saturated water (unsaturated solutions) (4a).
e) A piping system to facilitate the controlled flow of water or low saturated brine through aggregate cavities (leaching cavities). The piping system comprises: a leachate distribution ring (8), fed by a water pipeline, and a brine collector (9). Their couplings and fixtures make it possible to conduct and control the process of leaching salt rock sidewalls.

The salt rock sidewall leaching process can be conducted in many ways:

a) by periodically filling the aggregate mixture with a leachate and discharging it once the brine is saturated;
b) successively circulating a leachate through the aggregate mixture:
   - using different types of leachate circulation (upwards, downwards);
   - using different types of leachate flow (laminar or turbulent flow);
   - with the additional leaching augmentation effect by causing leachate turbulence using compressed air).

When using such a lining, the sinking of shafts in salt rock sections should be performed as follows:

a) excavate the shaft downwards along the entire salt rock section and secure it by an anchor lining, possibly featuring meshes made of a material that is resistant to mechanical corrosion;
b) below the salt rock layer, incorporate the lower base ring beam (3) Fig.10 on which the tubing-aggregate lining (5);will be erected
c) incorporate construction rings (6), at pre-defined spacing (9-15 m), to brace the structure of the shaft lining and divide the leaching chamber into shorter sections;
d) finish the lining column with the upper base ring beam directly above the salt rock layer.

Once the leachate (4a) can flow through the aggregate mixture (4), the salt rock sidewalls are being dissolved and create a post-leaching chamber (12), opening a new space for further rock migration while reducing the load on the internal tubing column (5).

Before this invention can be implemented, it will be necessary to conduct studies on the leaching process alone, and to construct an exploratory section of such a lining in a shaft whose profile features a rock salt strata. This task could be undertaken in one of the shafts featuring rock salt strata, located in the copper mining region of the Fore-Sudetic Moncline or in the Rybnik Coal District.

5. Summary

This work touches upon a very important aspect of underground construction in difficult geomechanical conditions. Mine workings in rock salt strata are exposed to increased convergence, thus requiring the use of structures that ensure the stability and desirable geometric parameters required for the workings to remain stable and function properly.

The paper presents the degree of convergence using the example of several Polish salt mines from various parts of the country. We have also presented a number of existing methods to solve this problem.

The new concept of a shaft lining design presented in this work relies on salt rock's unique property of leachability (solubility and scourability).

The key features of this lining and of the entire process of its load reduction include:

a) the internal waterproof column of the tubing lining made of cast-iron tubings, exhibiting a desirable load bearing capacity (thickness), constructed upwards and supported by a lower base ring beam;
b) the coarse-grained aggregate mixture made of magmatic rocks, which provides continuous support for salt rock sidewalls while also stabilising the internal column of the lining (its function being analogous to that of a road foundation or railroad ballast) and allowing fresh water to migrate and dissolve (leach) salt rock sidewalls in shaft workings;
c) the fact that the salt rock migrating towards the working through coarse-grained filler will cause the load on the tubing column to increase over time;
d) the fact that if the load on the lining is found to be too high – regardless of the method of determining the load, this being outside the scope of this work – periodic salt rock leaching should be initiated to reduce the stress in the lining;
e) the tubing-aggregate lining system should be equipped with appropriate measurement and inspection devices, as well as with fixtures and access walkways to conduct and monitor the leaching process, and provided with the equipment to replenish the aggregate filler behind the tubing column, if needed.

Further extensive research is needed on this new concept of a tubing-aggregate lining that provides the possibility of periodical salt rock sidewall leaching. Such research has been partly completed by Kamiński (Kamiński, 2018) at the AGH University of Science and Technology in Kraków and will be the subject of future publications.

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