TECHNICAL TRANSACTIONS 4/2017
CZASOPISMO TECHNICZNE 4/2017

CIVIL ENGINEERING

DOI: 10.4467/2353737XCT.17.046.6357

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Effect of salt mining on land surface

Wpływ górnictwa solnego na powierzchnię terenu

Abstract

The author discusses the issues associated with the changes of land surface shaping, caused by underground mining of salt. The characteristic of salt mining is essentially different from that of mining of other types of minerals, which is associated with salt's physical properties of salt rock mass. Consequently, the effects of underground salt mining that appear on land surface, although well known from other types of mining, are essentially different in dynamics and development in time. Most certainly, mining effects also depend on salt mining methods. Our analysis allows us to conclude that land surface deformations do not have to cause menace provided that proper technical and technological procedures are observed. The mistakes made in the salt mining art and practice may not be generally corrected and often end in mining catastrophes.

Keywords: salt mining, operating effects, mining land category

Streszczenie

W artykule omówiono zagadnienia związane ze zmianą ukształtowania powierzchni terenu, jakie wywołuje podziemna eksploatacja soli kamiennej. Specyfika górnictwa solnego w istotny sposób odbiega od górnictwa innych surowców mineralnych, co wynika z cech fizycznych górotworu solnego. W związku z tym efekty górnictwa solnego ujawniające się na powierzchni terenu, mimo iż są znane z górnictwa innych surowców mineralnych, istotnie różnią się dynamiką i przebiegiem w czasie. Niewątpliwie na skutki tego oddziaływania ma także wpływ sposób pozyskiwania soli. Prześledzenie przykładów pozwala na stwierdzenie, że przy zachowaniu właściwego reżimu techniczno-technologicznego powstające deformacje wcale nie muszą być problemem. Błędy popełnione w sztuce wydobywania soli są na ogół nie do naprawienia i najczęściej kończą się katastrofą górniczą.

Słowa kluczowe: górnictwo solne, wpływy eksploatacyjne, kategoria terenu górniczego

1. Introduction

Each form of mining is associated with the occurrence of negative effects in the natural environment. The types of such effects are characteristic for particular mining methods, and the effects are different in the cases of open-pit or underground operations, or solution mining which is also a form of underground mining. Salt mining is rather based on underground extraction, although particular methods are quite diverse.

Polish salt mining is proud of its nearly eight centuries of history. Salt was or has been extracted in four regions in Poland:

- southern (Wieliczka–Bochnia Foothills);
- central (Kłodawa and Inowrocław in the Kujawy region);
- western (near Polkowice);
- northern (the Bay of Puck area).

A number of salt extraction methods was developed during centuries. We can distinguish three basic groups of such methods:

- traditional underground mining, initially with the use of primitive tools and presently with the application of blasting and cutting machines;
- leaching (dissolving salt with fresh water) conducted in underground workings;
- leaching through boreholes drilled either underground or from land surface.

Each of those methods leads to the occurrence of workings of specific dimensions and shapes. However, the operation of gravitation forces causes that caverns are subjected to convergence. Without going into the details of the process, we can say that the appearance of the convergence effects on land surface is a question of time. Such effects are demonstrated by the change of shape and of hydrogeological relationships etc. Consequently, the natural environment can be affected (e.g. in visible replacement of vegetation species) and land use may also dramatically change, owing to mining menace [7, 11].

2. Mining menace: land surface shape effects

Generally speaking, mining menace refers to the damage caused by mining operations associated with the extraction of minerals. The range of damage is often fairly extensive, from rock mass and land surface deformations to disturbance or destruction of surface structures. This paper will discuss only the issues relating to land surface deformations caused by underground salt mining.

Land surface deformations triggered by mining operations, especially those with the use of underground mining methods, can be divided into two groups:

- the first one is identified owing to the type of mutual relationships of extraction and its influence exerted on rock mass and land surface (being direct, indirect, or secondary influence);
- the second one refers to the types of consequential deformations (continuous or discontinuous).

Direct effects include, as we can guess, the relocation of rock mass towards the excavation voids. The movement generates further rock mass deformations around workings (mainly in their roof and wall areas, less often in their floor areas), which are later reflected on land surface. Indirect effects result from direct extraction influences: they can appear outside the area affected by direct mining effects. The disturbance of hydrogeological relationships can be an example of that process. Secondary effects concern the consequences of continuous mining in the rock mass that has been affected by previous extraction, as well as land deformations appearing on the areas of old and retired mines [3].

Continuous land deformation consists in the process that does not cause visible disturbance of soil or rock compactness. Most often, that type of deformation is demonstrated by the appearance of sinkholes, but also sporadically by land elevation. Discontinuous deformations are of surface type (craters, depressions, or sinkholes) or linear type (fractures, cracking, or landslides).

The types of deformations depend on a number of factors. The most important of them include the following:

- the geological form of the deposit being extracted (e.g. layered sediments or salt domes);
- geological structure (in particular, roof rock mass) and tectonics;
- depth of mining;
- total height of workings (in a given cross-section);
- mining field dimensions;
- methods of workings' liquidation.

In the case of salt mining, we deal with both continuous and discontinuous deformations. Although continuous ones do not pose considerable threat, the discontinuous ones usually lead to mining catastrophes. Such phenomena are not rare since the salt rock mass is exposed to destructive influence of water which penetrates underground workings, owing either to the mistakes made in mining practice or the selection of inadequate extraction technology, and can flood a mine in a short time. 36 salt or potassium mines were flooded in Germany in 1851–1951, within several or about a dozen of years after their implementation, and 61 others were stopped, owing to a considerable water hazard. Besides, those mines were flooded soon after they had ceased to operate [14]. Serious problems with salt mine operation were also suffered in Poland, causing liquidation under emergency procedures (the "Kronprinz" Salt Mine in Inowrocław (1911) and those in Wapno (1977) and Łężkowice (1987)). When possible threat was predicted, a planned liquidation procedure was applied only to the "Solno" Salt Mine in Inowrocław (1997). The Bochnia and Wieliczka Salt Mines have also been subjected to planned partial liquidation, with the priority to protect the most valuable landmark workings.

3. Categories of mining areas

Owing to the types of discontinuous deformations (rock mass cracking, land subsidence etc.), the areas affected by such deformations are basically disqualified as potentially useful for development purposes. Reclamation of such lands is a long-term and expensive process, without any guarantee as to durable and complete elimination of hazards. Consequently, such post-mining lands can be used only in the way that would not pose any threat to human life or health.

Underground mining is dealing with mostly continuous types of direct mining effects on a daily basis. Those include land subsidence caused by sagging of the layers close to land surface. In mining practice, land subsidence maps are applied. They are produced on the basis of either actual surveys, or predictions applying the Budryk-Knothe theory (which is currently most frequently used in world mining). However, such tools are only auxiliary because land subsidence may not be decisive for certain forms of development. It is the indicators characterizing the sinkhole geometry that are of key importance [15]:

- maximum land slope: T_{max}, mm/m;
- minimum land curvature radius (convex or concave): R_{min}, km;
- extreme horizontal land deformation: ε_{extr}, mm/m.

Fig. 1 shows a graphic interpretation of particular surface deformation indicators.

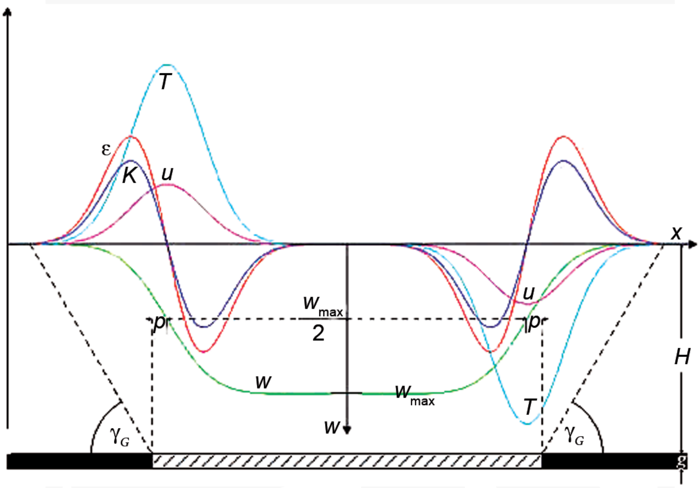

Fig. 1. Surface deformation indicators: their distribution over a mining field: *w* – subsidence, *T* – slope, *u* – horizontal displacement, ε – horizontal deformation, *K* – curvatures, *p* – mining field boundary, γ_G – angle of main influences, *H* – mining depth, *g* – layer thickness

Categories of mining areas are distinguished depending on specific indicator values, see Table 1.

Land is qualified under a specific category in respect of particular indicator values, with the most beneficial indicator assigning an area to the highest category. Nevertheless, other types of categories are also applied to mining land categories, assuming the qualification criteria separately for each indicator, e.g.: I (*T*), II (*R*), and I (ε).

As our structural development experience suggests, a mining area qualified to the Categories of 0 and I is refers to the land which is fully useful for development purposes. However, a number of restrictions apply to the areas belonging to Categories II and III, in reference to both existing and newly designed structures. The lands qualified to higher categories are not basically suitable for any development purposes.

Table 1. Mining area categories

Mining land category	Land deformation indicator values		
	slope T [mm/m]	curvature radius R [km]	land deformation ε [mm/m]
0	$T < 0.5$	$\lvert R \rvert > 40$	$\lvert \varepsilon \rvert < 0.3$
I	$0.5 < T < 2.5$	$40 > \lvert R \rvert > 20$	$0.3 < \lvert \varepsilon \rvert < 1.5$
II	$2.5 < T < 5.0$	$20 > \lvert R \rvert > 12$	$1.5 < \lvert \varepsilon \rvert < 3.0$
III	$5.0 < T < 10.0$	$12 > \lvert R \rvert > 6$	$3.0 < \lvert \varepsilon \rvert < 6.0$
IV	$10.0 < T < 15.0$	$6 > \lvert R \rvert > 4$	$6.0 < \lvert \varepsilon \rvert < 9.0$
V	$T > 15.0$	$\lvert R \rvert < 4$	$\lvert \varepsilon \rvert > 9.0$

4. Salt mining methods

Generally, salt mining methods belong to two types: dry and wet processes [6].

The dry method consists in salt rock cutting by blasting or mining tools and machines. Several extraction systems have been designed under that method (e.g. longwall caving, or chamber mining). Currently, the proper dry room-and-pillar method, with blasting, is applied in the "Kłodawa" Salt Mine. The other salt mine using the dry method in Poland, although with the operation of cutting combines, is the "Polkowice–Sieroszowice" Mining Company. In that case, the room-and-pillar system is practiced. Looking back at past operations, dry methods were also applied in the Wieliczka, Bochnia, and Wapno Salt Mines, with such systems as longwall caving, with conveyor belt transportation (Bochnia), or chamber cutting (Bochnia, Wieliczka, and Wapno). In addition, dry method works were conducted in Inowrocław to make preparations to proper wet extraction processes.

The wet (or leaching) methods are based on dissolving salt deposits with fresh water. Brine obtained by the process is subjected to evaporation to regain salt. Wet methods are applied in three options. The first one, which is currently used in Poland, consists in sprinkling the salt deposit in the virgin salt rock with a nozzle system. That process allows to form workings with specific dimensions and shapes by proper nozzle operation. In that case, the workings system is apparently similar to that obtained by dry methods. The second option, which is also currently applied, relies on dissolving salt rock in the so-called leaching plants, or chambers where salt is dissolved in stagnant water. After specific density has been reached, brine is pumped out and the chamber filled with fresh water. Both options were applied in the Wieliczka, Bochnia, and Inowrocław Salt Mines. The third option, called solution mining, starts with drilling boreholes from either land surface or underground workings towards salt deposits, followed by mounting pipes in the boreholes. Pipelines are designed to inject fresh water under pressure and collect brine, with various salt saturation. Fully saturated brine is transported for further processing, while unsaturated brine is subjected to a process designed for obtaining full saturation. Salt leaching through underground boreholes was applied in the Bochnia and Inowrocław Salt Mines, while the system of leaching from land surface was used in Barycz and Łężkowice (retired salt mines), and presently the process is continued in cavern leaching in Mogilno, Góra, and Kossakowo.

As this short review indicates, quite diverse methods are used in salt extraction. Those processes depend on physical properties of salt rocks which are quite different than those of other types of rocks.

5. Peculiarities of salt rock mass affected by mining and the mining effects on land surface

Each method of mineral extraction, in particular those concentrated underground, interferes with the original rock mass equilibrium. Violation of equilibrium causes generation of a secondary state of equilibrium and that leads to the changes in the state of stress and deformation on workings' boundaries [8]. Consequently, the rock mass displays a tendency to relocate towards the workings (free space underground). That movement can be limited by the application of mining support systems. Such phenomena are generally observed in coal, copper, and other types of mines. Those phenomena are associated with the term of workings' stability understood as a capability to maintain shape and location. Loss of stability is visible in the occurrence of rock falls, mainly from the workings' roofs, or wall convergence.

Those processes also occur in the salt rock mass that is subjected to the same forces. Nevertheless, that type of rock mass is characterized by certain properties that are essentially different than those of other types of rocks: salt rock mass displays rheological features, or elastic-viscous-plastic ones. Without going to details, we will mention the practical consequences of salt rock mass dissimilarity. Salt rock mass, or rather the workings within, is characterized by long-term stability and they often do not require any classical support systems. The salt chambers of the landmark salt mines (e.g. in Bochnia or Wieliczka) are good examples of that, similarly to younger workings in currently operated salt mines (e.g. in Kłodawa). We should mention here that those workings are very large in size which is not the case of mining other kinds of minerals. Salt mining is rather free of workings' roof rock collapses, except for some local slides in the form of salt blocks separated from roofs or walls. However, convergence is quite well visible in workings. In the initial phase of workings' existence, the convergence process is the quickest and it slows down with time. Despite such processes, we can recognize that workings are fairly stable and the convergence process will inevitably lead to complete closure of workings. However, after hundreds of years.

In the situation of the absence of roof rock collapses, no sudden rock mass destruction processes occur around workings. A fairly slow convergence process affects the surrounding rock mass, but the workings' boundary relocation process does not cause any dramatic cracking around the workings either. The extraction rate is also important in the process of rock mass relocation around the workings. In the case of other minerals (e.g. coal or ores), the extraction methods allow to obtain operating front progress, counted in dozens of metres a month, however, the progress of the chamber or room-and-pillar systems amounts to a dozen or several dozens of metres a year. Salt extraction from a standard chamber of 15 × 15 × 100 m takes about a dozen of months, which is a fairly long period for the attainment of the secondary state of equilibrium. In the case of the mining system with pillars between chambers, we observe the phenomena of creep and relaxation. Those phenomena result in fairly small rock mass relocations around the workings, which are visible in equally insignificant land surface subsidence. Since the vertical relocations of land surface are small, other forms of land surface deformation are insignificant as well. Thus land can be made available for structural development.

Such a course of processes is observed in the salt mines that are free of the phenomena causing sudden loss of stability, owing to the layout of the mine's workings. Nevertheless, a number of failures occurred in the salt mines in recent years, ending with the liquidation of salt mines under emergency procedures. Practically, such liquidations were mainly caused by the encroachment of fresh water or low-density brine into workings, which affected the salt rocks by dissolving them. The process of uncontrolled leaching of protective rock formations (pillars between chambers or shelves between corridors and chambers) propagates quite dramatically, causing quick rock salt destruction, followed by the rock mass collapse around the mining area. Land surface is affected by the appearance of discontinuous deformations which often bring about catastrophic consequences.

6. Experiences in the area of land surface protection, using the examples of Polish salt mines

Polish salt mining companies conducted or have been conducting mining operations within two types of salt deposits: salt seams (Bochnia, Wieliczka, Łężkowice, Barycz, Polkowice and Kossakowo) and salt domes (Inowrocław, Wapno, Kłodawa, Mogilno and Góra,). In addition, we can distinguish boulder salt rocks in which the oldest Wieliczka chambers were cut out. Dry and wet methods were applied in both seam and salt-dome deposits. That also concerned classical underground salt mines and extraction by solution mining. Consequently, we can say that the experiences of Polish salt mining are quite rich. Below, we will discuss particular underground salt mines, followed by solution mining operations, as they were established in the chronological order.

6.1. "Bochnia" Salt Mine

Brine was collected for obtaining salt by evaporation on the present lands of Bochnia even 3,500 years BC. However, only in the middle of the 13th century, the first underground workings were dug out. Salt mining continued until 1990 there, and the Salt Mine has been converted into a museum and spa facility. It is estimated that the total volume of the Bochnia workings amounts to ca. 4.3 million cubic metres [9]. The conclusion of extraction did not stop certain mining operations which mainly consist in the protection of the most valuable industrial landmarks and the liquidation of the lowest levels. During the centuries, collapses occurred in the mine and they caused local discontinuities on land surface.

In 1952, observation of land surface effects started, with regular expansion of the measurement benchmark network. However, only the measurements taken since 1972 are valid for drawing conclusions. Fig. 2 presents land surface subsidence in 1997–2015.

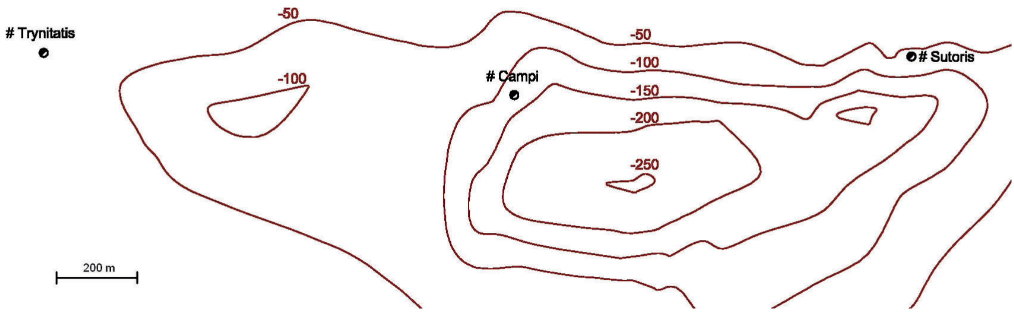

Fig. 2. Land surface subsidence in Bochnia in 1997–2015, based on observations

We can infer from Fig. 2 that the maximum subsidence reached about 250 mm in the past 18 years, and the sinkhole centre is located on the southern side of the mine's workings. Fig. 3 presents the projected land surface category, in respect of structural engineering needs.

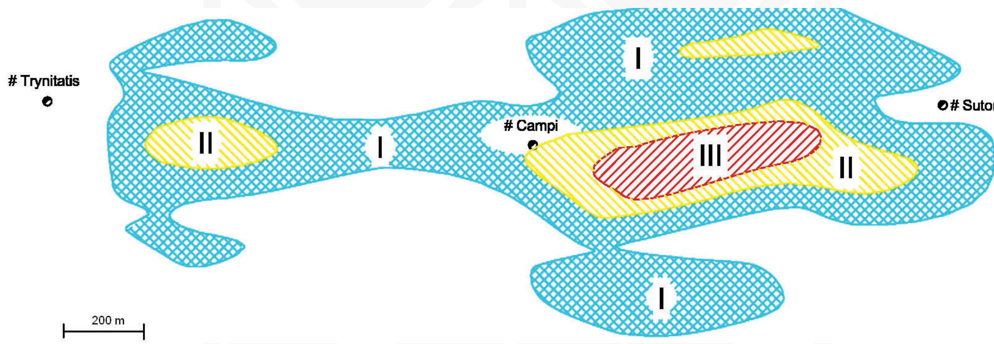

Fig. 3. The projected land surface category of land use for development purposes

Upon comparison of both figures, we can conclude that the northern section of subsidence affects the projected land surface category of land use for development purposes. Presently, it is difficult to estimate in what timeframe particular categories will be obtained. The forecast states that the least beneficial situation should affect the urbanized municipal areas, dominated by dispersed development.

6.2. "Wieliczka" Salt Mine

The "Wieliczka" Salt Mine is almost contemporary of the Bochnia one. However, both salt mines are quite different at least in their geological structures. The "Bochnia" Salt Mine was based on seam salt deposits, while the earliest mining activities started on a boulder salt deposit in the "Wieliczka" Salt Mine. Other types of salt formations were discovered later underneath, and deep mining operations started after the boulder had been extracted. Finally, ca. 7.5 million cubic metres of voids have been produced [9]. A considerable proportion of workings is not available any more, owing to rock mass degradation (convergence, collapses etc.).

Presently, mining activities are continued on the liquidation of post-mining voids that could affect the landmark sections of the salt mine. Liquidation by filling proceeds vertically, down to the lowest levels, and horizontally, from the peripheral sections to the centre of the salt mine. In the past, catastrophic occurrences were recorded owing to fairly shallow workings. Those events could have stopped further mining operations, as they were demonstrated by discontinuous deformations on land surface. The last dangerous collapse happened nearly twenty-five years ago when water flooded the Mina cross-corridor, resulting in fairly serious damage of surface structures.

Land surface observations started in Wieliczka in 1926. 1,500 measurement benchmarks have been set until present day. However, only the measurements that have been recorded since the 1960's represent documentary value. The previous ones were not accurate enough since some benchmarks had been destroyed. Fig. 4 shows a fragment of the mining area map, with the subsidence isolines of 1970–2015, while Fig. 5 presents the projection of the category of land usability for development purposes.

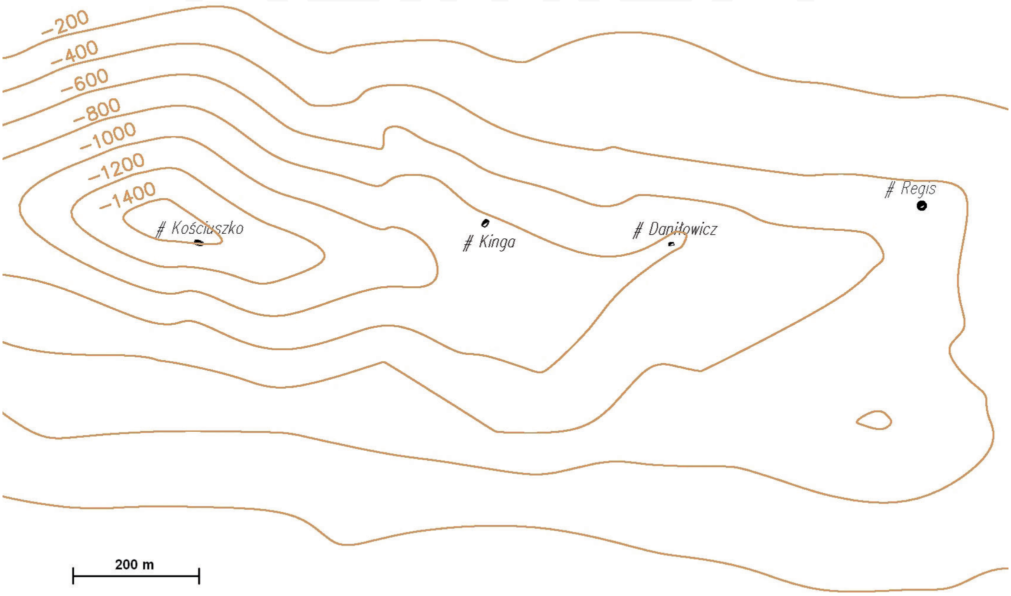

Fig. 4. Fragment of the mining area map, with the subsidence isolines of 1970–2015

The analysis of both figures leads to the conclusion that the majority of sinkholes that reached even 1,500 mm during the monitoring period, is correlated with the projected category of land usability for development purposes. Presently, the area for which Category II is projected is characterized by scarce and dispersed development.

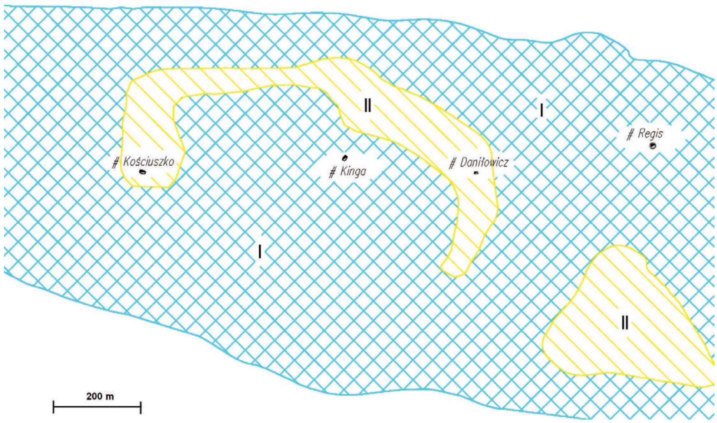

Fig. 5. Projected category of land usability for development purpose

6.3. "Kronprinz" and "Solno" Salt Mines in Inowrocław

The discovery of salt dome structures in the Kujawy region in the 19th century resulted in the opening of the first underground salt mine in the area in 1871. Salt was extracted there by the wet method. In 1907, water inflow forced the miners to close down the plant. Deformations in the form of cylindrical sinkholes, with lateral surface area of several hundred square metres each, appeared on land surface. The northern transept of the Annunciation Church collapsed in 1909 (Fig. 6) and a sinkhole, with the surface area of ca. 1,400 m^2 appeared, which quickly ruined several residential buildings (Fig. 7).

However, brine extraction continued from the flooded workings and even a solution mining process was implemented there. Brine pumping had to be stopped in 1933 in view of the appearance of new and extensive damages on land surface. Unfortunately, no surveying measurements were conducted on land surface and only photographs show the consequences of salt mining.

The conception of starting a new mine was developed after the "Kronprinz" Salt Mine had been abandoned. It was implemented in 1923 under the name of "Solno". Wet process was applied there in 1932, and about 15.4 million cubic metres of voids were leached until 1986 [10]. The decision of the mine liquidation by flooding, with brine and post-leaching waste filling, was made in reference to the events relating to the salt mine in Wapno (see below). The liquidation process was conducted in 1986–1992. It is hard to say even today whether that decision was right or wrong.

Fig. 8 (left hand side) shows the surface subsidence isolines of Inowrocław in 1952–1992. The "Solno" Salt Mine was responsible for that mining effect, although some rather limited influence of the "Kronprinz" Salt Mine cannot be excluded either. Maximum land subsidence reached ca. 300 mm in that period. The subsidence isolines of 1992–1995 after flooding (right hand side of the same figure) look quite interesting. The sinkhole reached 6 mm at the lowest point, although elevations of about 5 mm also appeared there, probably as a result of the changes in hydrological relationships underground and close to the surface.

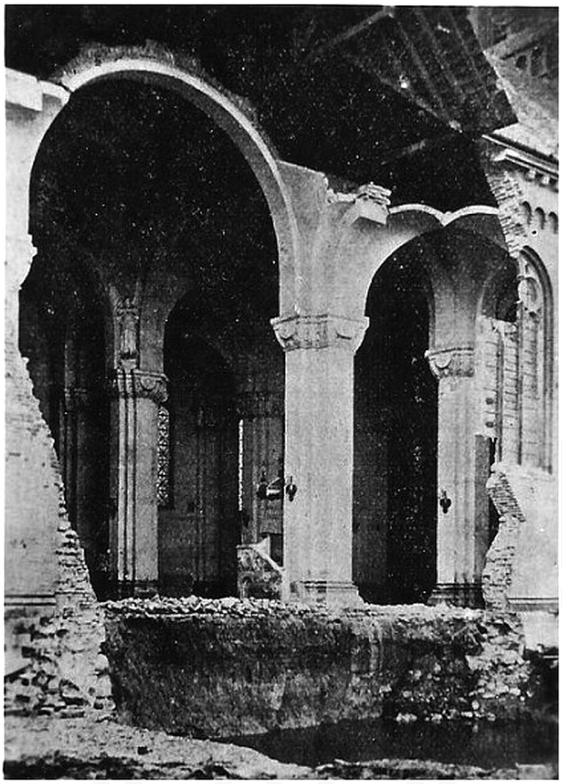

Fig. 6. Annunciation Church with a destroyed transept [17]

Fig. 7. Fragment of the sinkhole [17]

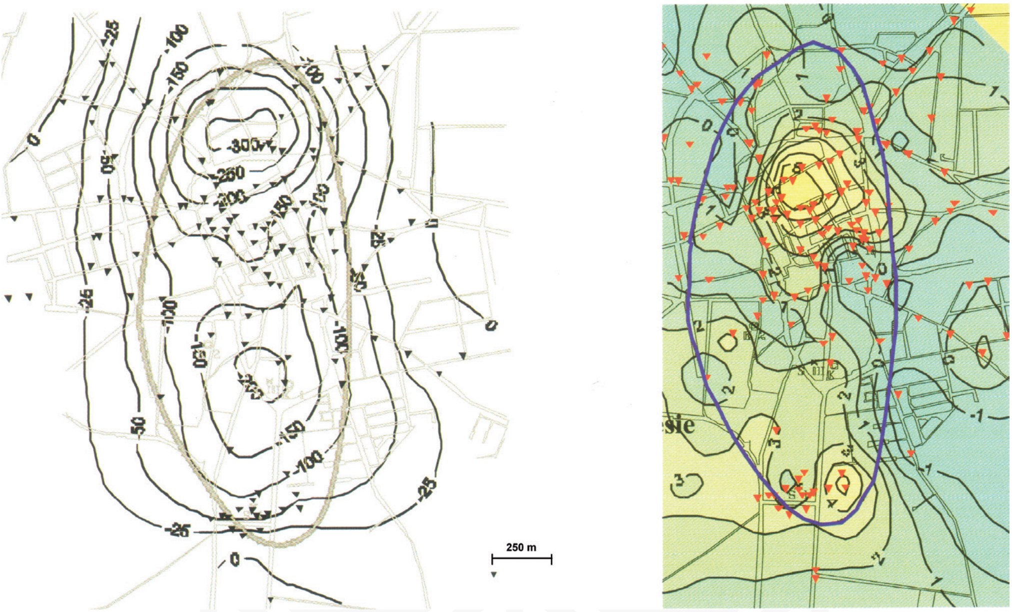

Fig. 8. The subsidence isolines of 1952–1992 (left) and 1992–1995 (right) [10]

The sinkhole and elevation areas developed there, right in the centre of Inowrocław, the town with typical urban structures. However, no significant mining menace was recorded there. Local deformations within the town caused delineation of a zone in which new capital projects are subjected to special design and construction procedures, similar to those that apply to the areas affected by mining menace.

6.4. Salt Mine in Wapno

The origin of that salt mine goes back to 1829. Initially, it was an open-pit gypsum mine, but the mining operations went underground later. Only after nearly 80 years, salt deposits were discovered below the gypsum layer, and the salt mine was constructed in 1911. It is obvious that the gypsum cap over a salt dome had been mined for several dozens of years! Such an operation would be recognized today as an elementary salt mining practice error.

The salt mine continued its proper chamber mining process at 8 of 13 designed levels, from Level III to Level X. The occurrence of sinkhole was identified on land surface. It reached its maximum value of about 600 mm after 40 years of mining (Fig. 9).

The decision of expanding mining to the new Level III was adopted in the 1970's and that decision caused significant consequences. A number of mistakes were made when salt mining was started through a considerably degraded gypsum cap. A sudden water inflow started into the workings at Level III in 1977. The intensity of encroachment was so strong that the whole salt mine was flooded within several weeks. It was estimated that about 30,000 m^3 of water flew into the mine at the rate of 2,000 m^3/min., within the first 15 minutes. The protective rock mass was quickly leached causing multiple discontinuous deformations on land surface, in the form of huge sinkholes and cracking. About 50 buildings were damaged (Fig. 10) including a multi-family residential house, and about 1,400 residents had to be evacuated.

The case of the salt mine in Wapno was the largest mining catastrophe in the history of Polish salt mining.

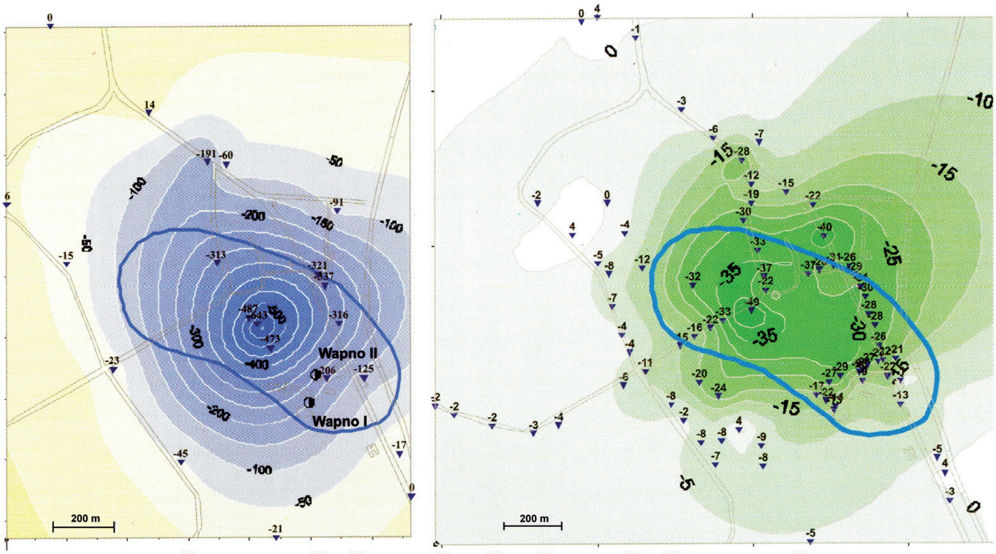

Fig. 9. The subsidence isolines of 1952–1992 (left) and 1992–1995 (right) [10]

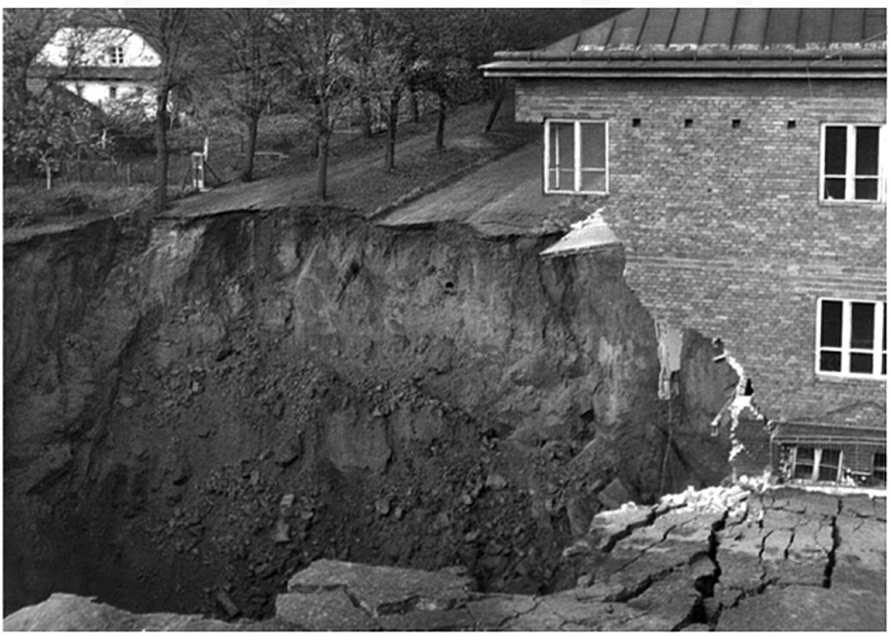
Fig. 10. Consequences of the catastrophe in the salt mine in Wapno [16]

The recent phenomena associated with land subsidence were recorded on the area in 2007 and 2010. Sudden linear, discontinuous deformations appeared there in the form of cracks. Unfortunately, there are justified fears that Mother Nature will show its power again in the future. Land reclamation issues have not been resolved until today. The local government intends to change the zoning plan and redesignate lands for other socially useful purposes [12].

6.5. "Kłodawa" Salt Mine

The "Kłodawa" Salt Mine is unique in Poland since it is based on salt domes and applies the dry mining method. It was implemented in 1951, and the first salt production was obtained in 1954. The salt mine has been conducting salt extraction for more than 60 years. About 18 million cubic metres of voids were dug out during that period.

The salt mine has been operating a surface monitoring system since its beginning [1]. The first surveying network was implemented in 1952, with about 70 benchmarks distributed on the area of ca. 6 km^2. The network was expanded in 2011 and reached 280 benchmarks on the area of ca. 44 km^2. The measurements revealed the development of a large area land subsidence, with two centres corresponding to Mining Fields 1 and 2. The largest sinkhole developed over Mining Field 2 in 1978–2011, owing to its size, and it reached ca. 180 mm. The other centre of Mining Field 1, with the depth of ca. 80 mm, is shown in Fig. 11. The sinkhole dimensions are probably associated with the vertical and horizontal sizes of the respective mining fields.

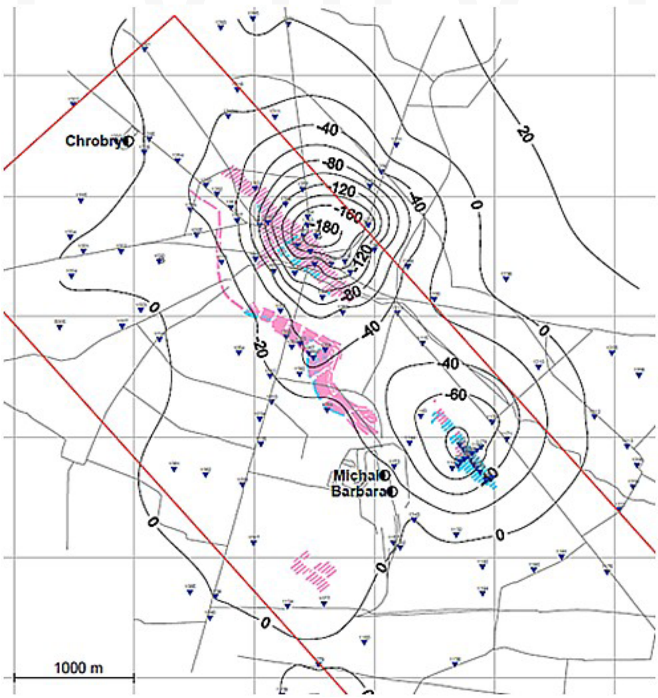

Fig. 11. Vertical relocations of land surface measured in 1978–2011 [5]

As to land management of the area subjected to the largest subsidence, zoning plans cover the centre of Kłodawa, located above Mining Field 2. However, the areas over Mining Field 1 are used for farming purposes. Presently, the salt mine holds a mining concession until 2019, but the management has applied for a prolongation until 2052. The plans indicate that mining will be continued within the currently exploited fields but at lower levels than the existing ones. It is also assumed that magnesium-potassium salt will be extracted in Mining Field 7, which was only partly extracted by excavation of two small chambers.

Presently, the areas affected by mining consequences are generally classified under Category 0 and locally under Category I. The mining land category ranges, as predicted for 2052, are shown in Fig. 12.

If salt extraction is continued until 2052, we can expect that the area belonging to Category I will be extended, with the appearance of areas covered by Category II, in the period of several dozens of years after 2052. However, considering the time of such development, the issue is not considered to be problematic now.

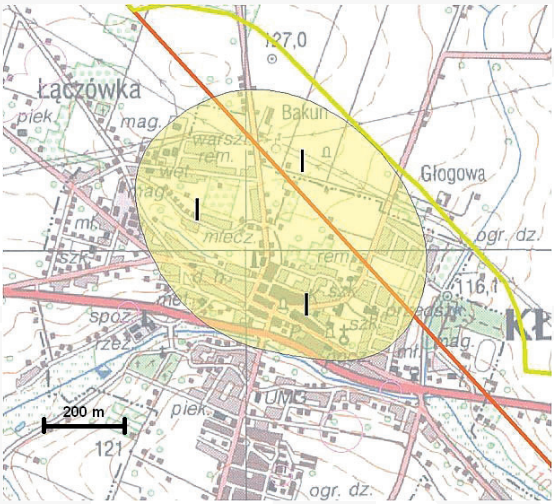

Fig. 12. Projected mining land category ranges in 2052 [5]

6.6. "Polkowice-Sieroszowice" Mining Company

The salt mine has been extracting salt in the "Bądzów" field for more than 20 years. A layered salt deposit is located above the copper ore deposits. We can say that salt extraction is a side production, in parallel to copper mining. Salt is cut mechanically by the room-and-pillar method. Three mining levels have been designed, with the plan to continue mining during 50–60 years, with the output of 1 million tons a year. However, the copper ore deposits should be exhausted earlier (in about 20–30 years) and it would be hardly possible to maintain the plant facilities afterwards only for the needs of salt mining.

Possible salt mining effects are currently difficult to estimate because, despite its large capacity, the salt mine's output is limited to saleable quantities. The demand for salt depends mainly on weather conditions during the winter period. In addition, the mining effects have to be considered in the context of copper ore mining.

As specific analyses have demonstrated, the most pessimistic scenario, assuming complete extraction of only the "Bądzów" field deposit and filling of voids in 90%, the largest subsidence can reach a stable state at about 2.5 m (in about 150 years!). Almost the whole "Bądzów" field area will be covered then by Category I, with a small section qualified under Category II in the northern part of the field. However, if copper mining effects are also taken into consideration, land subsidence will reach nearly 4 m, with a considerable field area to be qualified under Category II and a small section qualified under Category III in the northern part of the field [4]. The applicable future period scenario is so distant that the projected mining effects can be essentially limited because the scope of mining operations remains unknown.

6.7. „Barycz" Hole Salt Mine

The salt mine was operated in 1924–1998, using the solution mining method in a seam deposit. During that period, 980 operating and 44 exploratory boreholes were drilled. In total, ca. 10.5 million tons of salt was produced in the form of brine on 4 mining fields (Pagory, Centralne, Słoneczne, and Soboniowice). The boreholes were drilled from land surface, and an underground leaching process was applied, without cavern roof protection. That method contributed to the development of many large caverns out of control. The mining effects have the form of discontinuous deformations: multiple landslides and sinkholes [2]. The damages affected green areas, not developed land. Fig. 13 shows the distribution of sinkholes and land subsidence isolines, based on the observations conducted in 1926–1976.

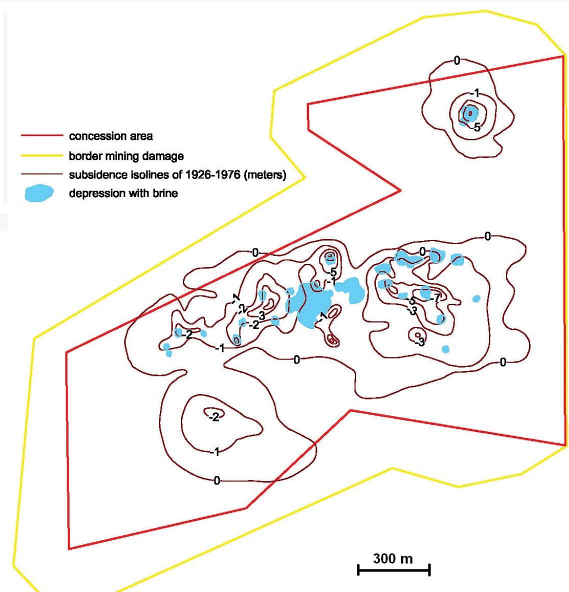

Fig. 13. The subsidence isolines of 1926–1976 and depressions with brine

Fig. 14. Municipal landfill construction on the Central Field (from archive Salt Mine "Wieliczka")

Fig. 15. Municipal landfill during operation (from archive Salt Mine "Wieliczka")

Partial chamber filling activities were conducted under a land reclamation project, which was a complex task, owing to the existence of uncontrolled connections between the chambers. In addition, surface reclamation works were completed. A municipal landfill was constructed in part of the Central Field that was subjected to the largest degradation. Fig. 14 presents the landfill development stages and Fig. 15 shows the condition during the landfill operation.

6.8. "Łężkowice" Hole Salt Mine

The "Łężkowice" Hole Salt Mine, using the solution mining method, was operated shortly in 1968–1988. Its liquidation took another twenty years and mainly concerned the liquidation of mining effects.

Brine was obtained by salt rock leaching, with two boreholes drilled from land surface for that purpose. Mining layout was designed with sets of caverns. Each set was composed of three caverns, 25 m in diameter each, distributed in a triangle 35 m apart. Consequently, the protective pillars were 10 m wide.

Mining was conducted without cavern roof protection and at small depth of 120–400 m below the ground level. Land subsidence appeared fairly soon, together with multiple sinkholes. Those resulted from specific geological structure of both deposit and overburden, causing a number of problems associated with the leaching structure of the designed caverns, as well as the mining method which was subjected to adjustments to current geological difficulties. Consequently, hydraulic connections were developing between the caverns, with the occurrence of unplanned caverns, rock mass cracking etc. After the rock mass collapse, the nearby Raba River was filled with brine containing about 1 million tons of salt, equivalent to about 15% of the total output of that salt mine [13].

After mining operations had been stopped, protective and reclamation works were implemented. The degraded land surface was fenced off and miners started to fill underground caves. Presently the land has been reclaimed and designed for farming purposes (Fig. 16).

Fig. 16. Fragment rehabilitated mining area (photo by K. Poborska-Młynarska)

However, the projections indicate that a whole selection of mining land categories will appear there in the future, from Category 0 to Category V (Fig. 17).

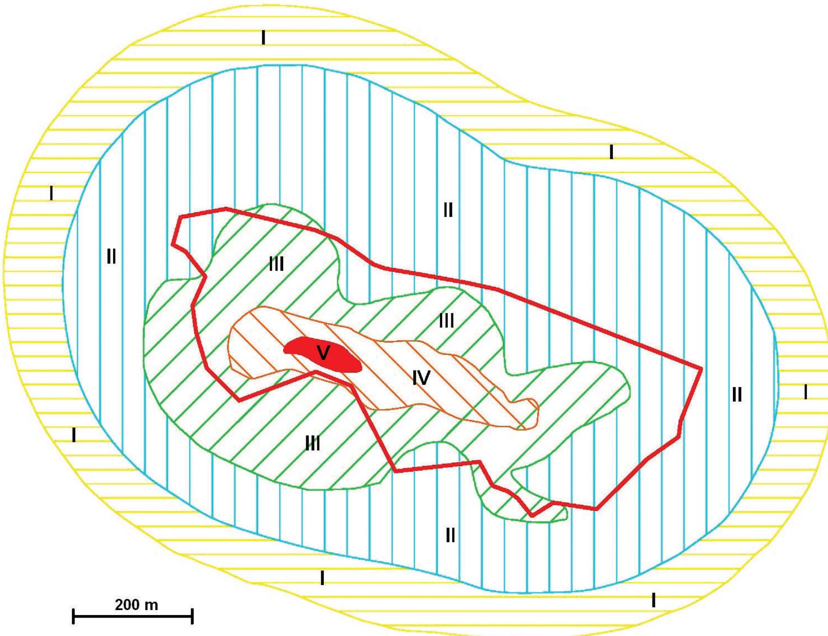

Fig. 17. Projected mining land category ranges in 2052

6.9. "Solino" Salt Mine in Inowrocław

The company has been operating two solution mining facilities in Góra (since 1968) and Mogilno (since 1987). The mines apply wet processes to extract brine from the salt domes in which caverns of ca. 50 m diameter and the depth of even more than 1,000 m are leached.

Upon our analysis of cavern stability, we concluded that the situation was exceptionally good as to geomechanical aspects. Firstly, caverns have always been filled with more or less saturated brine, which obviously influences wall stability. Secondly, the mining process applied there provides for cavern roof protection, with the use of solar oil. Its relatively thin layer effectively protects the cavern ceiling against uncontrolled leaching. The only hazard can be related to uncontrolled hydraulic connections between neighbouring caverns. To prevent that occurrence, protective pillars 100 m thick have been maintained.

After salt extraction, the caverns were turned into underground storage facilities for natural gas and liquid fuels. Consequently, the stored media constantly supports the cavern walls inside. Still, the caverns are subjected to the convergence process reflected in the occurrence of sinkholes on land surface. When analyzing the sinkholes one can conclude that subsidence is insignificant: up to several dozens of centimetres. That would not cause menace since the salt mine is situated on farmlands, with scarce farms, and thus the land has been qualified under Category 0.

7. Conclusions

This paper provides a review of all the salt mines which were or have been operated recently in Poland. Our first conclusion concerns mining catastrophes which are caused by:

- encroachment of underground water into workings;
- extraction of brine from flooded salt mines;
- loss of control over the solution mining process.

Each mining catastrophe is reflected on land surface, with more or less dramatic effects. The stories of sudden inflow of water into the Mina cross-corridor (1992) or upward propagating collapse of the Schmidt chamber (1960) in Wieliczka ended with a relative success. More tragic were the consequences of the salt mine flooding in Wapno (1977), contributing to the destruction of a town district, with the consequences showing and hurting still today. Similar phenomena were recorded in Inowrocław (1906–1911), although on a small scale. Also, the solution mining facilities in Barycz and Łężkowice caused extensive land surface devastation. Luckily, the mine locations were outside developed areas, although land reclamation took a lot of time and involved high expenditures. Those areas are still disqualified for development, despite recovery and reclamation operations.

Still, as our experience indicates, a salt mine does not have to be perceived as a source of land devastation, causing loss of valuable land features. Long-term mining activities, sometimes conducted even for centuries, lead to the occurrence of sinkholes where subsidence can be measured not only in centimetres, but also in metres. Nevertheless, we should consider the fact that the processes in question are distributed over long periods, which considerably reduces the scale and size of the properties that decide about the usability of land affected by mining for development purposes. Good examples of that are available in Bochnia, Wieliczka, and Kłodawa.

It seems that the background described here calls for a discussion among the geological, mining, and building circles whether the categorization of mining lands applied to coal and ore mine areas is equally adequate for salt mine areas. A similar issue can be raised in respect of land deformation projections which apply to very long periods. Practically, verification of such predictions will be possible a dozen or dozens of years into the future. Undoubtedly, it is necessary to conduct land surface monitoring activities on salt mining areas and, as far as possible, observations of the relocation of working's profiles. Such activities will contribute to the increase of our knowledge on salt rock mass and its movements in reaction to mining operations.

The author wishes to thank the following persons for their valuable assistance, advice, and data: Mr. Tomasz Migdas (KS "Bochnia"), Mr. Paweł Ulmaniec (KS "Wieliczka"), Prof. Kajetan d'Obyrn (former President of KS "Wieliczka"), Mr. Damian Kurdek (KS "Kłodawa") and Ph.D. Katarzyna Poborska-Młynarska (AGH).

This paper was prepared as part of statutory work No. 11.11.100.005.

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