AGH Journal of Mining and Geoengineering • Vol. 36 • No. 1 • 2012

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INTER-CHAMBER PILLARS IN POLISH SALT MINING — CHOSEN DIMENSIONING METHODS IN THEORY AND PRACTICE

1. Introduction

Polish post-war salt mining comprising of rock-salt mining by means of a dry method, is generally limited to four plants: already out of operation salt mines in Wapno, Bochnia and Wieliczka and the operative salt mine 'Kłodawa' Company Ltd., in Kłodawa. The perspective region to mine rock-salt is 'Polkowice-Sieroszowice', in Kaźmierzów, which belongs to KGHM Polska Miedź Company Ltd., in Lublin. The latter has been mining for almost 20 years. The salt deposit here are lying above a cupriferous layers, however this activity has only a research and recognition character.

The both mines operate in diametrically different mining and geological conditions, and the basic differences are the deposit formations where mining is performed. The Salt Mine 'Kłodawa" mines in salt diapir at the depth interval of about 400–750 m, whereas the Mining Plant 'Polkowice-Sieroszowice' in a bedded deposit at the depth of about 950 m. There are obviously more differences between the two deposits, but because of their extensiveness, they are not going to be mentioned in this paper.

At present, the basic system of salt mining is by means of a dry method, is the classical chamber system [4]. The system is applied in thick deposits of a bedded type and in diapirs. The essence of the system is based on the choice of chambers, which are about 40÷100 m long, up to 20 m wide and 30 m high. In Figure 1, the example of mining system by means of chamber system is shown.

In the instance of mono-layer mining, the chambers are separated with an inter-chamber pillar, whose width fluctuates around the dimension that equals the width of the chamber. In deposits of seam thickness, multilayer mining is possible, therefore, each chamber level is

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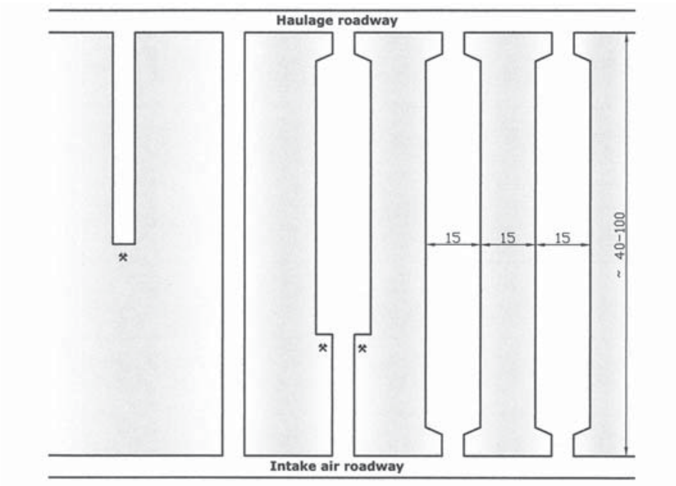

Fig. 1. Chamber system — floor projection

separated with an inter-level shelf (subject literature describes it as horizontal pillar). Inter--chamber pillars and inter-level shelves are to secure stability of rock mass, which surrounds the salt deposit (Fig. 2).

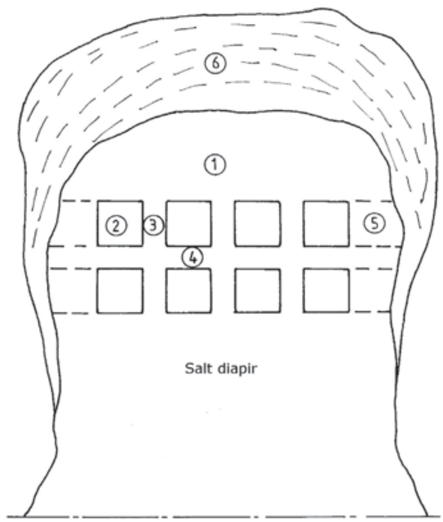

Fig. 2. Chamber system in salt diapir [4]
(1 — safety shelf, 2 — chamber, 3 — inter-chamber pillar,
4 — inter-level shelf, 5 — edge pillar, 6 — gypsum-anhydrite overlay)

The dimensions of each element of chamber system, i.e, chambers, pillars and shelves should be designed in such a way that does not allow damage to the newly created openings as well as neighbouring rock mass.

In the instance of saline from Kłodawa, this system is used in all mining fields. In this paper, all citations will refer to field nr 2, which is the biggest field in the mine and quite regularly cut. On upper layers, the standard dimensions of the chamber cross-section are 5×15 m, while inter-chamber pillars are 15 m wide, which makes that the distance between the axises of the chambers is 30 m (horizontal module). The thickness of the shelf is related to the distance of each inter-level (vertical module), which in all fields up to 600 m is 25 m, and below is 30 m. Because of safety, starting from level 630, the width and height of the chambers were decreased, which with a constant spacing of the axises of the chambers and the distances of each inter-level makes pillars wider and thicker with increasing mining depth shelves were left.

To outline the full picture of the mining systems used in the salt mine 'Kłodawa', so--called high chambers should be mentioned, which are located in field nr 2, on levels 525, 550 and 575, directly under the safety shelf. The width of these chambers is 15m, whereas the height is 30m, therefore, identification of these headings is by calling them 'high chambers'. 21 such chambers were made in the mine. The changeable height of their foundation on particular levels is related to the inclination of the safety shelf.

The third used system, which is relinquished at present, is the cylindrical chamber system. Cylindrical chambers, 18 in number, are located in the central and widest part of field 2, between levels 500–600. The chamber diameter is 24 m, whereas the inter-chamber pillar is 16 m in its narrowest place. The height of the chambers is differentiated; amounts to 75 or 100 m.

At the present moment, mining is conducted by means of flat chambers with the use of blasting engineering. From technological point of view mining is conducted by a roof-stepped system and floor-stepped system.

For the next few years, it should be expected that because resources are running out in the 'Kłodawa' mine, on mining market, the Mining Plant 'Polkowice-Sieroszowice' will appear as the salt producer with full rights (so, with the licence to mine it). Because of geological-mining conditions and attempts already made, it should be expected that also in that mine chamber system will be applied. As things are, actual knowledge of the dimensioning of chambers, pillars and shelves should be reconsidered, the more so as the planned mining will take place much deeper than it is at present in Kłodawa.

2. The chosen methods of inter-chamber pillars' dimensioning

The calculation of dimensions for different kinds of pillars in mining are connected with the existence of the mine right from the start. It begins with the stage of unproductive development, then development mining till mining. Each time the problem requires individual analysis of existing geological-mining conditions, which thus requires the appropriate calculation methodology. Because one universal method cannot be used. Its choice is influenced by load quantity working on the pillar and its geo-mechanical features. In particular, the latter factor is incredibly significant, considering the scatter of results related to rock strength parameters, which are obtained by laboratory testing and *in situ*.

The problem is widely-known and mentioned by many scientists who work on that issue, which consequently led to many hypotheses based on empirical and experimental considerations as well as mining practice. Each particular method should be approached to in a critical way, as often they refer to local characteristic conditions, therefore cannot be used on a large scale.

Some of the most popular chosen methods are presented below, which were used a few years before for dimensioning of chamber headings and undisturbed soils separating them from other chamber headings, and each particular method is supplied with the author's comment (WA).

All determinations used in the cited formulas are in accordance with the mentioned source records.

2.1. Protodiakonow Method[1]

Protodiakonow, in his scientifically described method of pillars' dimensioning between two dog headings, assumed that the weight of overlaying rocks counterbalances the growth of stresses in undisturbed soil on the both sides of the heading. To simplify his considerations, Protodiakonow assumed that those stresses spread along the straight line, and their sum makes triangle surface — Figure 3 (hatched area).

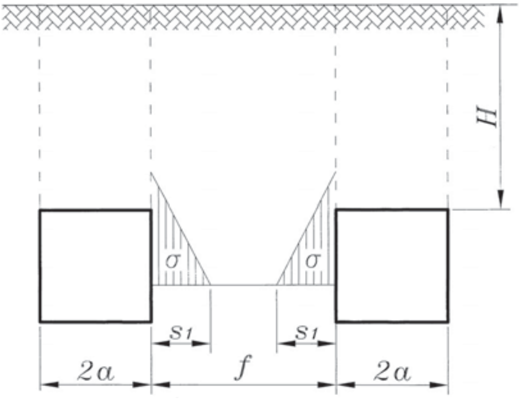

Fig. 3. Protective pillar between two headings

Therefore, from condition of equilibrium it result that:

$$\gamma \cdot H \cdot a = \frac{1}{2} \cdot \sigma \cdot s_1 \tag{1}$$

where:

γ — rock weight by volume, [N/cm^3],
H — deposition depth, [cm],

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1 According to source [5]

$2a$ — width of heading, [cm],
σ — stress growth in side of work, [N/cm^2],
s_1 — width of zone affected by increased stresses, [cm].

On the grounds of done experiments, Protodiakonow determined that:

$$\frac{\sigma}{s_1} = 0.73 \cdot \mu \tag{2}$$

where:

μ — coefficient of rock hardness according to Protodiakonow, interpreted as:

$$\mu = \frac{R_c}{10} \tag{2a}$$

where R_c – compression strength, [MPa].

After conformal transformation of equation (2) and substitution to equation (1) it is obtained:

$$\gamma \cdot H \cdot a - \frac{1}{2} \cdot 0.73 \cdot \mu \cdot s_1^2 = 0 \tag{3}$$

Thus, in a simple way, zone width formula is obtained s_1:

$$s_1 = 1.66 \cdot \sqrt{\frac{\gamma \cdot H \cdot a}{\mu}} \tag{4}$$

On the grounds of that, the minimal width of the pillar can be determined, which equals to double width s_1. Protodiakonow suggests additionally taking into consideration the factor of safety, whose value should amount to about 2. Finally, it means that the width of pillar f after allowing for formula (4) and suggestions of the author, should amount to:

$$f \cong 6.64 \cdot \sqrt{\frac{\gamma \cdot H \cdot a}{\mu}} \tag{5}$$

Comment on Protodiakonow method

Protodiakonow worked out the method for dimensioning of pillars located between two dog headings, taking into consideration only one strength parameter, which is derivative of compression strength. Dog headings because of their functions are relatively low, particularly in comparison with chamber headings. The practicability of this method for dimensioning of inter-chamber pillars is of little importance, as it is later shown in this chapter, the height of the pillar is of significant importance, which as a consequence transfers to its load capacity.

2.2. Stamatiu Method[2]

Romanian salt mining has a tradition several hundred years'old, therefore a lot of interesting experience can be expected in relation to the matter under discussion. Mihail Stamatiu was one of the scientists who did the research on salt rock mass.

Stamatiu investigated salt strength on cubic samples as well as on cuboidal samples of the base of a square. As the result of his observations, he drew up the following dependence:

$$R'_c = R_c \cdot \sqrt{\frac{l}{h}} \tag{6}$$

where:

R'_c — compression strength of cuboidal sample, [kg/cm²],
R_c — compression strength of cubic sample, [kg/cm²],
l — side length of sample base, [cm],
h — height of cuboidal sample, [cm].

In his consideration, he assumed that decompression zone is created around the salt chamber, whereas inter-chamber pillar transmits the load coming from overlaying beds only in central part d_2. The shape of decompression zone and diagram of pillar load is shown in Figure 4.

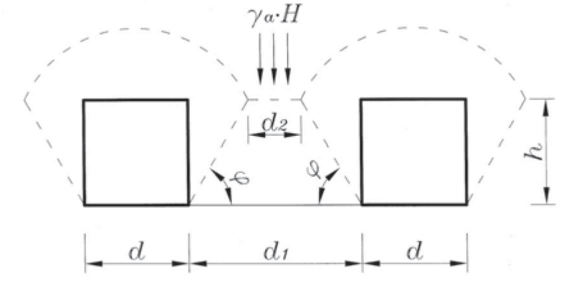

Fig. 4. Decompression zone around a chamber and pillar load according to Stamatiu [3]

On the grounds of that, in a simple way, a formula can be made to determine safe width of pillar's base d_1:

$$d_1 = d_2 + 2 \cdot h \cdot ctg\varphi \tag{7}$$

2 According to source [7]

where:

d_2 — width of central part of pillar, [m],
h — height of pillar, [m],
φ — angle of slip plane in the decompressed zone, [°].

The angle of slip plane in the decompressed zone is related to the angle of internal friction of the rocks surrounding heading ρ:

$$\varphi = 45^\circ + \frac{\rho}{2} \tag{8}$$

For central part of pillar with width d_2 strength condition takes form of:

$$\gamma_a \cdot H = R_c \cdot \sqrt{\frac{d_2}{h}} \tag{9}$$

where:

γ_a — unit volume of overlay, [t/m^3];
H — depth of chamber floor, [m].

Therefore, after simple transformation:

$$d_2 = \frac{H^2 \cdot \gamma_a^2 \cdot h}{R'^2_c} \tag{10}$$

Therefore, after substitution of equation (10) for formula (7) a formula is obtained that determines minimal width of pillar d_1:

$$d_1 = \left(\frac{H^2 \cdot \gamma_a^2}{R'^2_c} + 2 \cdot ctg\varphi \right) \cdot h \tag{11}$$

Comment on Stamatiu's solution

The solution of Stamatiu, in the face of contemporary underground experience, can be a bit doubtful in relation to the hypothesis that decompression zone is created around a chamber heading. If such a zone was created, then the roof of the heading should aim at creating a so called natural roof (so, big salt patches falling off the roof) while the loosening of rocks in the side wall part, particularly under the roof of the chamber. During that time, Polish experience shows that such a phenomena do not occur. Many years' stability of chambers is observed despite the lack of any lining. Perhaps, the period of observation is too short (a dozen or so, tens of years?), therefore, such a solution should be completed with a time ratio – the matter is in which way it should be used in the presented equation.

Taking into consideration all mentioned above and giving up hypothetical decompression zone, equation (11) with regard to factor of safety n would take form of [3][3].

$$d_1 = \frac{n^2 \cdot H^2 \cdot \gamma_a^2 \cdot h}{R'^2_c} \tag{12}$$

2.3. Metoda by Sałustowicz-Dziunikowski[4]

Sałustowicz and Dziunikowski, similarly to other scientists (e.g., p. [2, 7]), studied the dependence between the strength of the sample and its shape. They established that limit load capacity can be determined by the formula:

$$R = R_c \cdot \left(\alpha + \beta \cdot \frac{a}{h}\right) \tag{13}$$

where:

R — sample strength of given shape, [kG/cm^2]
R_c — sample strength of cubic shape, [kG/cm^2],
α, β — material constants, according to Sałustowicz-Dziunikowski for salt $\alpha = 0{,}75$, $\beta = 0{,}25$;
a — sample width, [m],
h — sample height, [m].

After substitution, formula (13) takes form of:

$$R = R_c \cdot \left(0.75 + 0.25 \cdot \frac{a}{h}\right) \tag{14}$$

While mining by means of the chamber system with long pillars, stresses in the pillar can be calculated with the formula:

$$\sigma = p \cdot \left(1 + \frac{l}{a}\right) \tag{15}$$

where:

p — primary stresses in rock mass, [kG/cm^2],
l — chamber width, [m],
a — pillar width, [m].

3 In formula (12) determinations used by Stamatiu were taken [7]
4 According to source [6]

Strength condition related to the strength of pillars, in which vertical compressive stresses occur, with giving consideration to factor of safety n and after transformation of formulas (14) and (15) it will take the form of

$$\frac{R_n}{n} \cdot \left(0.75 + 0.25 \cdot \frac{a}{h}\right) = \gamma \cdot H \cdot \left(1 + \frac{l}{a}\right) \tag{16}$$

where:

R_c — sample strength of cubic shape, [kG/cm^2],
n — factor of safety,
a — pillar width, [m],
h — pillar height, [m],
γ — weight by volume of overlaying rocks, [kG/dcm^3],
H — depth of chamber floor, [m],
l — chamber width, [m].

After appropriate transformation of formula (16) and ordering of its constituents, quadratic equation is obtained in the form of:

$$\left(\frac{0.25 \cdot R_c}{n \cdot h}\right) \cdot a^2 + \left(\frac{0.75 \cdot R_c}{n} - \gamma \cdot H\right) \cdot a - \gamma \cdot H \cdot l = 0 \tag{17}$$

Equation (17) possesses discriminant $\Delta > 0$, in that case, two roots are the solution, whereas the one that makes sense, fulfills the condition $a > 0$. Therefore, the searched width of the pillar can be written as follows:

$$a = \frac{-\left(\frac{0.75 \cdot R_c}{n} - \gamma \cdot H\right) + \sqrt{\left(\frac{0.75 \cdot R_c}{n} - \gamma \cdot H\right)^2 + 4 \cdot \left(\frac{0.25 \cdot R_c}{n \cdot h}\right) \cdot \gamma \cdot H \cdot l}}{2 \cdot \left(\frac{0.25 \cdot R_c}{n \cdot h}\right)} \tag{18}$$

Comment on the method by Sałustowicz-Dziunikowski

The method given by the authors is based – similarly to the method by Kegl [2] or Stamatiu [7] — on the determination of dependence between the compressive strength of the sample and its shape. The obtained formula was used to determine the allowable stresses, which can occur in the pillar, and that is a simple way to determine its width. However, the authors lay down the condition that this method requires further research, including for the models built of a few or even several chambers, which as a consequence is to lead to the of use the obtained solution in practice. It follows that the authors critically approached the proposed solution, pointing out the further course of research.

2.4. Method by Hwałek[5]

The author, in his considerations, takes into account the surface of pillars and chambers, with reference to the strength of the salt rocks that built the pillar, including the depth of mining. He proposed the following formula:

$$c = \frac{H \cdot \gamma \cdot \cos\alpha}{10 \cdot K_c} \tag{19}$$

where:

c — pillar surface to surface of pillars and chambers ratio,
H — depth of mining, [m],
γ — unit weight of rock overlay, [T/m^3],
α — angle of deposition of strata (medium), [°],
K_c — crushing strength of rock material from a pillar, [kG/cm^2][6].

The width of pillars and chambers should be chosen in such a way in order to fulfill the condition:

$$c < \frac{b}{a + b} \tag{20}$$

where:

a — width of mined chamber, [m],
b — width of protective pillar, [m].

The author proposes that the maximum width of a chamber is 20 m while minimal width of a pillar is 10 m. In this way, he determines the minimal value of factor c, therefore formula (20) takes form of:

$$c = \frac{b}{a + b} = 0.333 \tag{21}$$

Treating factor c from formula (21) as maximum border value (c_{max}), then the value of factor c calculated with formula (19) can be considered as correct if it fulfills the condition:

$$c_{max} = 0.333 > c \tag{22}$$

5 According to source [1]
6 In author's evaluation (WA) probably it refers to compressive strength R_c

The author advises that such accepted dimensions of chambers and pillars should be checked with approximation way for pillar compression strength. Therefore, overlay weight Q along chamber axle (on 1 m length) should be calculated:

$$Q = H \cdot \left(b + 2 \cdot \frac{a}{2}\right) \cdot l \cdot \gamma \cdot \cos\alpha \tag{23}$$

And then determine the pressure in the pillar:

$$p = \frac{Q}{F} \tag{24}$$

Where F — pillar surface on 1 m of chamber length, [m^2].

Checking factor of safety n according to formula:

$$n = \frac{K_c}{p} \tag{25}$$

Comment on the method by Hwałek

The method proposed by Hwałek [1] is, as a matter of fact, very similar to the method by Kegel [2, 7, 8]. The ratio determined by formula (19), Hwałek refers to the surface of pillars and chambers, whereas Kegel with analogical formula, advises calculation the ratio of pillars' surface to total mining surface. Thus, the given method is more conservative in comparison with Kegel's method, therefore such results should be expected, which would suggest using wider pillars than it results from Kegel's formula [2].

3. Comparison of theoretical results with existing mining practice

In order to verify the methods discussed above, a series of calculations were done according to the assumptions made for movement solutions in field 2, in Salt Mine 'Kłodawa' Company Ltd. As it was mentioned before, there are three kinds of chambers in this field: flat chambers, which constitute about 90% of all mining headings in this field, and several high and cylindrical chambers. A further course of consideration will refer to flat chambers whose dimensions of cross-section change with the depth of mining. Juxtaposition of cross-section dimensions for chambers, pillars and shelves is shown in Table 1.

As it was mentioned before, the decrease in cross-section dimensions of chambers aimed at safety considerations. Probably, it used to have certain theoretical grounds, but with the passage of time, it is difficult to find out the premises, which the designers followed, apart from intuitional reasons resulting from mining practice.

TABLE 1
Cross-section dimensions for chambers, shelves and pillars in field 2

Level	Horizontal module	Vertical module	Chamber dimensions		Shelf thickness	Pillar width
			width	height		
	[m]	[m]	[m]	[m]	[m]	[m]
Up to 600	25	30	15,0	15,0	15,0	15,0
630	30	30	13,4	13,4	16,6	16,6
660			13,0	13,0	17,0	17,0
690			12,6	12,6	17,4	17,4
720			12,2	12,2	17,8	17,8
750			12,0	12,0	18,0	18,0

In Figure 5 below, the diagram showing the real width of pillars on particular levels in field 2 is presented and also corresponding with them theoretical calculations done on the grounds of the formulas: (4) — Protodiakonow, (7) — Stamatiu A, (12) — Stamatiu B, (18) — Sałustowicz-Dziunikowski, (19) and next — Hwałek.

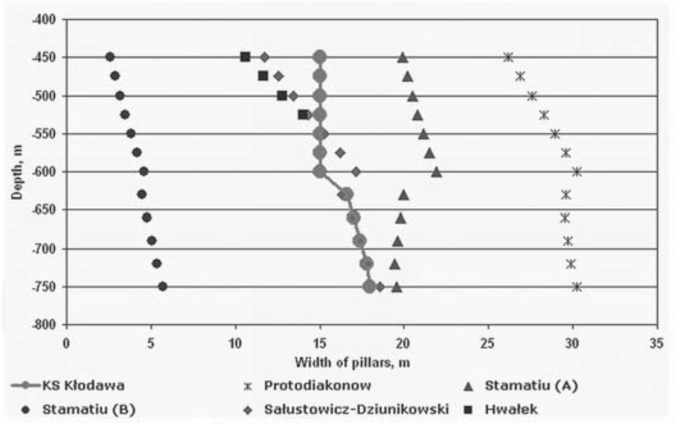

Fig. 5. Comparison of theoretical width of pillars with real dimensions with assumption of factor of safety $n = 1$

For calculations the following parameters of rock mass were taken: overlay unit weight $\gamma = 23$ kN/m^3, compression strength of salt $R_c = 20$ MPa, angle of internal friction $\rho = 30°$. The depth of particular levels, the dimensions of chambers and pillars were taken from Table 1. At the same time, it was assumed that factor of safety is $n = 1$.

Analysing the diagram above, it can be stated that the results obtained by means of the formulas given by Protodiakonow [5] and Stamatiu [7] do not comply with the real conditions observed in the mining environment. It results from the diagram that the real width of pillars is too small, so they should be damaged. The situation observed in the mine does not confirm these hypotheses, therefore the both can be treated as useless.

Concluding further, it can be stated that in the both cases, the authors assumed the occurrence of decompression zone around the heading, which in fact, do not occur, and it was confirmed by present mining observations. In such case, Stamatiu's formula of omitting decompression zone (12) has its grounds, and the obtained results show that there is much safety in reserve [3].

The next formula given by Sałustowicz-Dziunikowski for upper levels (so for smaller depths) can be considered to be useful, but for intervals 550÷600 it would indicate pillars' instability. Below level 600, the results are convergent with the real ones but considering the assumed factor of safety $n = 1$, the pillars should work on load capacity border, and as a consequence, there should be observed the phenomena related to approaching loss of stability. Because of the fact that such phenomena are not observed, this method can be eliminated from further consideration.

The last of the considered methods — the method by Hwałek — fulfills the assumptions only for chambers/pillars founded up to level 575, in some measure, automatically being eliminated for bigger depths. Therefore, using the formulas given by Hwałek becomes quite limited.

Because of the fact that, in practice, all engineering calculations are done with consideration of factors of safety, on the next stage, that factor was considered and its value accepted as $n = 1,5$, as the recommended one by International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The results are illustrated in the next diagram, shown in Figure 6.

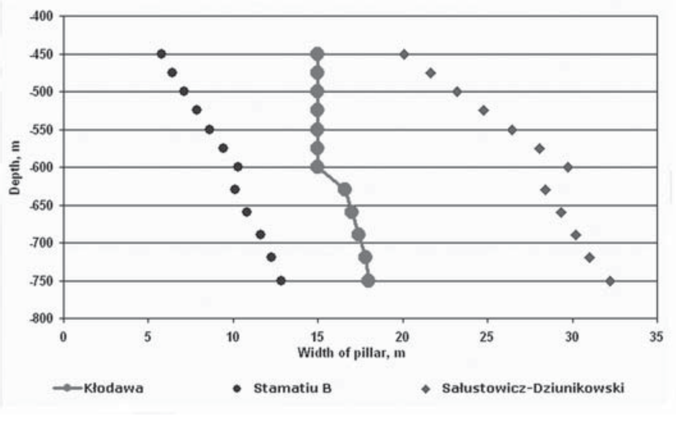

Fig. 6. Comparison of theoretical width of pillars with real dimensions with assumption of factor of safety $n = 1.5$

The results obtained eliminate the formula given by Sałstowicz-Dziunikowski from further consideration, as in calculations before the obtained results were 'on borderline'. The methodology given by Hwałek, was completely eliminated as it does not fulfill the initial condition, which was given by the author — formula (22). The formula given by Stamatiu

(12) defended itself, though factor of safety n = 1,5 was accepted, it still shows certain 'margin' of the pillar's width, which obviously improves factor of safety.

4. Summary

The given considerations showed that none of the presented methods are suitable for real conditions observed in a mine every day. The methods described, though, recognized around the world, which is reflected in professional literature, should not be used in practice in that specific case, as they lead to significant over-dimensioning of their width.

Similarly, Woyciechowki [8] expresses his opinion and states that rarely in practice, dimensions of chambers and pillars are determined on the grounds of theoretical solutions, whereas determination of their dimensions should be done basing on underground observations of pillars and identifying the occurrence of scratches, fissures and chips of rock fragments from undisturbed soil, which will testify redistribution of stresses. Furthermore, he advises taking into consideration the observations made in order to decrease the dimensions of headings, or widen the width of pillars, while designing next headings.

In the light of contemporary knowledge, it is clearly seen that none of the methods consider the rheology of salt, which significantly differs from other kinds of rocks. The proposed theoretical solutions treat the salt medium as elastic, whereas its plasticity and viscosity should be considered. It is also of great importance to know geo-mechanical properties of salt, each time in the site under research, as present experience shows, the obtained values can have scattering effect on results. The geological structure of salt rock massif itself is equally important, and particularly its petrological diversification, which within one deposit can be significantly variable, thus has influence on strength parameters.

The great possibility of solving the problems discussed above are in numerical methods that can more precisely allow modeling the phenomena that occur in the salt mass, particularly in three dimension (3D). However, often general-purpose solutions should be found satisfying, which are caused by a lack of detailed geological research, and therefore, inability to model precisely variability of rock mass. So far, attempts in this domain have shown that the obtained degree of accuracy is satisfying, which is reflected in practice.

Paper compiled within statutory work no. 11.11.100.370.

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