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METHODS OF DETERMINING ROCK MASS FREEZING DEPTH FOR SHAFT SINKING IN DIFFICULT HYDROGEOLOGICAL AND GEOTECHNICAL CONDITIONS

OKREŚLENIE GŁĘBOKOŚCI ZAMRAŻANIA GÓROTWORU DLA POTRZEB GŁĘBIENIA SZYBÓW W TRUDNYCH WARUNKACH HYDROGEOLOGICZNYCH I GEOTECHNICZNYCH

Methods of determining the depth of rock mass freezing for the purpose of shaft sinking in solid rocks in difficult hydrogeological and geomechanical conditions are analyzed in this paper. There are presented factors on the basis of which the freezing depth can be determined in heterogeneous rocks media. The author focuses on the source of problems with establishing parameters used for defining the freezing depth. A method of interpreting hydrogeological and geomechanical source data is presented on two examples of weak and medium compact sandstones freezing for the purpose of shaft sinking in the Legnica-Głogów Copper Mining District, south-western Poland. Moreover, a general algorithm for determining the rock mass freezing depth is given. The following main criteria of freezing depth evaluation have been assumed: hydraulic conductivity values, porosity, rock quality designation index *(RQD)* and Protodiakonow's rock compaction index. The outflow of drilling fluid in the exploration borehole was taken into account as a complementary criterion. The practical use of the algorithm was exemplified by a geological profile.

Keywords: rock mass freezing, strata freezing, freezing depth, shaft sinking, water-bearing layer, LGOM

W wyniku trwającego rozwoju prognozuje się rosnące zapotrzebowanie na surowce mineralne. Kontynuowane jest wydobycie rud polimetalicznych w Legnicko–Głogowskim Okręgu Miedziowym (LGOM) w SW Polsce i niewykluczona jest eksploatacja złóż rud polimetalicznych w Polsce NE. W praktyce głębienia szybów stosowana jest metoda mrożenia selektywnego. Metoda ta wymaga dokładnego określenia bezpiecznej głębokości wytworzenia płaszcza mrożeniowego. W pracy zaproponowano metodykę postępowania w celu określenia głębokości zamrażania w skałach zwięzłych o trudnych warunkach hydrogeologicznych i geomechanicznych, szczególnie kiedy napór hydrostatyczny wody wynosi kilka MPa.

Dokonano oceny czynników oraz ich efektów wpływających na określenie bezpiecznej głębokości zamrażania wodonośnych skał zwięzłych w górotworze oraz zestawiono schematycznie (Fig. 1). Na dwóch przykładach przedstawiono sposób interpretacji źródłowych danych hydrogeologicznych i geomechanicznych w celu określenia głębokości mrożenia górotworu. Przykłady dotyczą mrożenia górotworu dla

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szybów w LGOM: GG-1 i SW-4. W celu określenia głębokości zamrożenia skał dla obu szybów istotne są poziomy wodonośne występujące do głębokości około 650-700 m w piaskowcach triasu dolnego. Poziomy te występują w strefach słabo i średnio zwięzłych, silnie spękanych piaskowców o zróżnicowanej jakości i wytrzymałości na ściskanie. Wpływa to na ich zwiększoną porowatość i przepuszczalność (Tabela 1 i 3). Stosunkowo niskie wartości wskaźnika spękania rdzenia wiertniczego (*RQD*) i współczynnika zwięzłości skał Protodiakonowa (f_d) wskazują, że w tej strefie głębokości występują niekorzystne warunki geomechaniczne (Tabela 2 i 4). Głębokość zamrożonego górotworu dla potrzeb głębienia szybu GG-1 metodą selektywnego zamrażania winna wynosić 690 m, czyli do spągu strefy wodonośnej wytypowanej na etapie wstępnej analizy. Dla szybu SW-4 winna wynosić 650 m. Głębokości te uwzględniają 10 m zapasu miąższości skał – koniecznego ze względów bezpieczeństwa.

Zaproponowano ogólny algorytm postępowania w celu określania głębokości zamrażania górotworu dla głębienia szybów w skałach zwięzłych, w trudnych warunkach geologicznych (Fig. 2). Etap 1 ma na celu określenie przedziału głębokości występowania poziomów wodonośnych w skałach zwięzłych, które będą przedmiotem dalszej analizy. Analiza szczegółowa (Etap 2) polega na sprawdzeniu spełnienia kryteriów oceny przez poszczególne poziomy wodonośne. Kryteriami oceny głębokości zamrażania są odpowiednie wartości dopuszczalne współczynnika filtracji (*k*), porowatości ogólnej (*n*), wskaźnika spękania rdzenia wiertniczego (*RQD*) i współczynnika zwięzłości skał Protodiakonowa (f_d).

Przyjęte wartości dopuszczalne są podane w postaci dwóch wartości danego parametru. Odnoszą się one nie tylko do wartości maksymalnej (*k* i *n*) lub minimalnej (*RQD* i f_d), ale także do ich wartości średniej, spośród wartości prezentowanych w raportach z prac badawczych w otworach wiertniczych. Takie elastyczne podejście wynika z potrzeby uwzględnienia naturalnej zmienności wartości tych parametrów w górotworze, szczególnie szczelinowym. Wystarczy że jeżeli trzy kryteria analizy są spełnione, to należy zakwalifikować daną strefę wodonośną do zamrożenia. W przypadku oceny wykazującej, że jedynie dwa kryteria charakteryzujące dany poziom wodonośny są spełnione, sprawdza się dodatkowe kryterium oceny (Etap 3). Tym kryterium jest wystąpienie odpływu płuczki wiertniczej z otworu badawczego, w zakresie głębokości odpowiadającym ocenianemu poziomowi lub w jego bezpośrednim sąsiedztwie. W przypadku, gdy warunki geologiczne w najgłębszym poziomie (oznaczonym jako N), są na tyle korzystne że nie musi być zamrażany, to należy przejść do Etapu 4 procedury – czyli do sprawdzenia kryteriów oceny kolejno w coraz płytszych poziomach (N-1, N-2,…). Sprawdzanie spełnienia kryteriów oceny w takiej kolejności ma na celu uniknięcie ryzyka, że poziom który powinien być zamrożony, mógłby nie zostać wytypowany. Ilustruje to przykładowy schematyczny profil geologiczny (Fig. 3). Profil obejmuje cztery poziomy wodonośne wytypowane na etapie oceny wstępnej. W wyniku analizy szczegółowej przeprowadzonej zgodnie z algorytmem, wskazano dla każdego z nich, który winien być objętym zamrożeniem, a który tego nie wymaga. Proponuje się aby do głębokości spągu najgłębszego poziomu wodonośnego objętego mrożeniem dodać 10 m miąższości skał, jako dodatkowe zabezpieczenie.

Przedstawiony algorytm postępowania mającego na celu określenie głębokości zamrażania górotworu dla potrzeb głębienia szybów w skałach zwięzłych, w trudnych warunkach geologicznych, może być zastosowany szczególnie w LGOM. Ze względu na dążenie do bardziej uniwersalnego charakteru przyjętych kryteriów oceny, metodyka może być również stosowana w innych rejonach złóż. Prezentowane podejście może stanowić podstawę dalszych prac badawczych, gdyż możliwe jest uzupełnienie algorytmu o inne kryteria oceny w przypadku znacznej odmienności warunków geologicznych w innych rejonach lub jego modyfikacja.

Słowa kluczowe: zamrażanie górotworu, głębokość zamrażania, głębienie szybów, poziom wodonośny, LGOM

1. Introduction

At this stage of civilization development the demand for natural resources is expected to increase or at least stay on the same level. This applies to non-ferrous metals or rare metals (e.g. *Ti*, *V*). The exploitation of complex polymetallic ores is carried on in the Legnica-Głogów Copper Mining District (LGOM), in the northern part of the developed deposit (1000-1250 m deep). The planned production of the reserve and prospective deposits located at 1250-1500 m

(Speczik et al., 2007; Wirth et al., 2007) reaches deeper than shallow, gradually depleting beds of the lithosphere (Kicki et al., 2007). Moreover, complex ore mining can be also realized in the north-eastern Poland. For the sake of these deposits Chudek et al. (1987) proposed: the shaft sinking method, depth of rock mass freezing, mining system, ore treatment and beneficiation as well as waste storage and utilization methods with no substantial environmental impact. As a result, a few (or more) shafts may be performed in Poland in the coming 15 or so years.

The selective freezing method is used in the shaft sinking practice, mainly for the deep shafts. In this method freezing holes are required to occupy a vertical position (Poprawski, 1988) and the safe depth at which the frozen cover is formed has to be defined thoroughly. The depth of the rock mass freezing has to be determined to specify the depth required for sealing of all water-bearing layers, which could become a potential water hazard. The author proposes a unique method of determining the freezing depth in solid rocks under difficult hydrogeological and geomechanical conditions, especially when the water hydrostatic thrust is several MPa.

2. Evaluation of factors having effect on freezing depth determination in solid rocks

In order to determine the freezing depth of deeper water-bearing layers in solid rocks, it is essential to know the real values of hydrogeological and geomechanical parameters. In heterogeneous conditions of a rock mass, the scale of measurement is observed to affect the obtained results (Carlsson et al., 1990; Pistone, 1990), i.e. in the case of large and heterogeneous strata their geomechanical properties may differ from those determined for small rock samples in lab conditions. This scale is larger for fissured rocks as compared to a more homogeneous porous system.

Rovey & Cherkauer (1995) and Schulze-Makuch et al. (1999) noticed that under a wide range of geologic media the hydraulic conductivity (*k*) value increases with scale of measurement until a tested volume of rock is reached, beyond which *k* remained constant. This means that point measurements of *k* are not always representative of more than local values. The approach proposed by Kidybiński (2004), with a rough method of determining the scale ratio based on rock strata quality, using the rock quality designation index *RQD*, is useful for practical mining tasks.

The fault zone permeability assessment is also a factor which has an influence on determining the freezing depth in water-bearing solid rocks. Factors determining whether a fault zone acts as a conduit, semi-conduit or barrier system were analysed by Caine et al. (1996). However, to correctly assess the permeability degree of the fault zone in the further distance from the shaft is a difficult task.

Hydraulic conductivity values estimated with the use of drilling methods in survey boreholes should be treated as only approximate becouse instead of long-term pumping tests for at least several days, the hydraulic conductivity values are determined with the use of rather imprecise methods, i.e. depletion water from the borehole, slug test or measurement with a drill stem tester. The real hydraulic conductivity values, a basic parameter indicating rock's ability to conduct water, may vary significantly. It is therefore possible to revise (increase or lower) drill-based or lab-specified values of some physical and mechanical features of the rock masses in order to obtain values for the design that would increase the safety of driving mining headings.

The above issue is also connected with the fact that real values of rock hydrogeological parameters in the proximity of sunk shaft will be higher during the sinking process than values established with the use of drilling methods and subsequently presented in hydrogeological and geological-engineering reports. This results from the fact that borehole tests are conducted in an almost intact rock mass, prior to the sinking and shooting operations. For this reason the depth of rock mass freezing was not determined solely from average values of hydrogeological parameters obtained after preliminary tests. Instead, their maximum values registered in a given zone were also taken into consideration. When it comes to geomechanical parameters, their minimum values determined from the strength tests should also be analysed and then included in the geological-engineering report.

These maximum hydrogeological and minimum geomechanical values are essential as in the case of water inflowing to the shaft, hydraulic cleaning may take place and the space in the currently filled fissures and cracks may open up. In such case the rock mass quality near the shaft may deteriorate due to water thrust under a hydrostatic pressure of several MPa. As a consequence, these extreme values taken for assessment will be indicative of the actual conditions around the shaft.

The water flow in sandstones depends on their fissuring. Consequently, crack areas should be regarded as areas of possibly greater groundwater inflows. Unfavourable conditions for mechanical rock mining exist in compact rocks, e.g. sandstones due to their compaction and strength, which suggests mining with the use of explosives. Vibrations and tremors brought about by the use of explosives during sinking operations cause increased rock fracturing, growth of the fissure apertures and consequently bigger water inflow. This uncontrollable effect escalates if the water-permeable layer exists in brittle rocks which are characteristic of low compaction and lower strength.

Such a process took place in LGOM during the R–XI shaft sinking when a water inflow of 5 MPa occurred at a freezing depth of 635 m. The rate of inflow increased to 3.0 m^3/min and continued for 15 months. In a piezometer located 7.7 km away, screened in the Tertiary sands, the groundwater drawdown amounted to 6.4 m (Kalisz & Niedbał, 2004).

The above mentioned fact points to good hydraulic interconnections between water-bearing layers in the Middle Triassic rocks reaching even an overlying aquifer in the Tertiary sandy deposits. Fast water inflow is caused by mechanical rock erosion due to the fast movement of water at a hydrostatic pressure of several MPa. As far as determining of safe rock freezing depth is concerned, the author attributes importance not only to hydrogeological properties such as hydraulic conductivity and porosity, but also to geomechanical parameters: rock quality designation index *RQD* which characterizes the rock quality and Protodiakonow's rock compaction index.

Factors and their effects on safe freezing depth of water-bearing solid rocks in a rock mass are summarized and classified schematically in Fig. 1. However, while sinking a shaft in dusty sand aquifers, their thickness and presence of quicksand are the only factors which make the use of the freezing method indispensable.

3. Examples of determining rock mass freezing depth for shaft sinking in the Legnica-Głogów Copper Mining District (LGOM)

Source data on geological conditions in the areas of GG-1 and SW-4 shafts were acquired from the documentation of geological conditions registered in boreholes S-439A (Table 1 & 2)

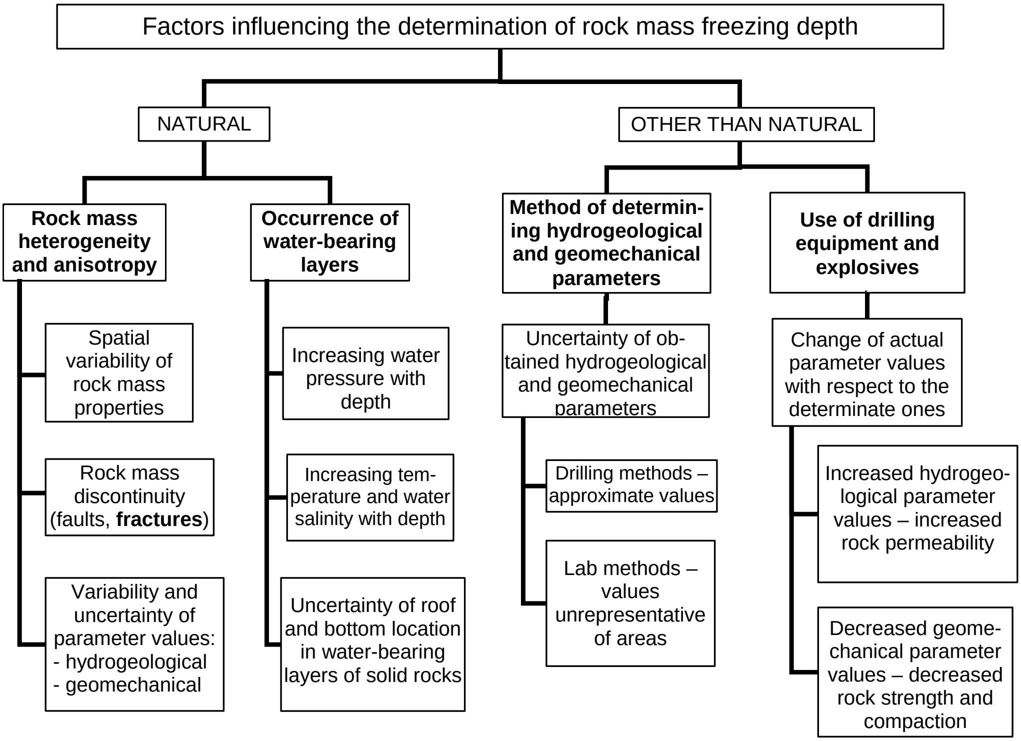

Fig. 1. Factors and their effect on the process of determining rock mass freezing depth for shaft sinking in solid rocks

and S-373A (Table 3 & 4). The author refers to them to a limited extent, only when illustrating geological conditions that determine relevant rock mass freezing depths for shaft sinking.

Determining of freezing depth for the GG-1 shaft

TABLE 1

Selected values of some hydrogeological parameters of rocks in a selected part of the Middle Buntsandstein, borehole S-439A (based on Gruszecki et al., 2009; Wąsik et al., 2009)

Depth [m]	Hydrostatic pressure [MPa]	Porosity (*n*) [%]	Hydraulic conductivity (*k*) [m/s]		
			mean based on hydrogeological tests	mean based on geophysical logging	maximal based on geophysical logging
537.5-638.5	4.3-5.1	15.6-24.5	$6.37 \cdot 10^{-7}$	$1.37 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$
638.6-689.5	5.3	8.5-26.9	$3.36 \cdot 10^{-7}$	$1.92 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$

TABLE 2

Values of selected geomechanical parameters and simplified geomechanical rock characteristics of a selected part of the Middle Buntsandstein, borehole S-439A (based on Supel et al., 2009)

Depth [m]	***S****	***RQD**** **[%]**	**f_d* [-]**	***n**** **[%]**	**R_c* [MPa]**	**Rock characteristics**
645.9-652.5	min mean max	44	1.78	16.98 17.18 17.51	22.37	weak and medium compaction[1] poor quality[2] very low strength[3]
652.5-672.0	min mean max	82 87 92	2.78 3.16 3.92	6.56 9.85 12.85	56.27 71.60 88.97	medium compaction[1] good quality[2] average strength[3]
681.0-700.0	min mean max	57 67 76	4.17	5.98 8.20 9.36	88.25 97.19 108.62	medium compaction[1] average quality[2] average strength[3]

* S – statistic parameters, *RQD* – rock quality designation index, f_d – Protodiakonow's rock compaction index, *n* – total porosity, R_c – compressive strength,

[1] – according to Protodiakonow's classification, [2] – according to *RQD,* [3] – according to M. Borecki's rock mechanical classification, based on value R_c

Based on the analysis of litho-stratigraphic profile of boreholes, practical experiences from shaft sinking in the northern part of LGOM and analysis of factors determining uncertainty of data included in geological documentations, Duda & Duda (2009) revealed that, from the perspective of determining the freezing depth, the most important are several water-bearing layers which exist at a depth of about 700 m in Lower Triassic sandstones (Table 1 & 2). The layers exist in zones of weak and medium compaction, strongly fractured sandstones of varying quality and compressive strength. It impacts on their slightly higher porosity and permeability. Decreased values of rock quality designation *(RQD)* index and Protodiakonow's rock compaction index (f_d) show that unfavourable geomechanical conditions can be found at this depth.

The analysis of hydrogeological conditions reveals that deeper layers are recharged by groundwater leakage through the upper, shallower zones, also through low permeable beds (Duda & Duda, 2009). A hydraulic contact of deeper and shallow water-permeable layers is also possible due to the flux of water through crack zones running along the tectonic faults. As a result, there might be a danger of increased and long-term water inflow during the exposure of such zone to mining works. It was decided that the possible danger of increased water inflows during shaft sinking came from two water-bearing layers in sandstones and they were interpreted as one hydraulically connected zone with a total thickness of 152 m. In the S-439A borehole they are located at 537.5-689.5 m of depth. Similarly, in the S-439B borehole the zone occurs at a depth of 536.8-679.6 m. It should also be noted that while drilling the S-439A borehole a quick drilling fluid outflow occurred at depths of 630.0-640.0 m, and in the S-439B borehole at depths of 627.0-659.0 m (Gruszecki et al., 2009; Wąsik et al., 2009).

Accordingly, it can be concluded that the depth of fully frozen rocks for the purpose of the GG-1 safe shaft sinking with the selective freezing method in difficult hydrogeological and geomechanical conditions should be 690 m, i.e. to the bottom of the water-bearing zone which is the subject of the discussion. It includes a 10 m thickness margin required for safety reasons. When the working face in the shaft approaches this layer, the aperture of fissures and cracks may increase, new fractures may be created and capped fissures may open up. If the zone is not frozen completely, it is possible to activate the existing water-bearing layer. An additional cause is a drilling-related uncertainty of determining accurate depth of water-permeable layer bottom if the underlying rocks have similar lithological features.

Freezing depth determination for SW-4 shaft sinking

TABLE 3

The hydraulic conductivity determined with different methods and porosity of rocks in a selected part of the Middle Buntsandstein, borehole S-373A (based on Dziedziak & Bielawski, 2005)

Depth [m]	**Hydrostatic pressure [MPa]**	**Porosity (*n*) [%]**	**Hydraulic conductivity (*k*) [m/s]**			
			depletion	**slug test**	**drill stem tester**	**recovery test**
557.0-562.0	3.7	12.8-19.2			$7.9 \cdot 10^{-8}$	
572.0-630.0	3.7	3.9-16.5	$1.1 \cdot 10^{-6}$			$1.1 \cdot 10^{-6}$
640.0-645.0	4.0	9.2-13.0	$2.4 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$		

TABLE 4

Values of selected geomechanical parameters and simplified geomechanical rocks characteristics in a selected part of the Middle and Lower Buntsandstein, borehole S-373A (based on Supel & Pluta, 2005)

Depth [m]	**S***	***RQD** [%]**	**f_d* [-]**	***n** [%]**	**R_c* [MPa]**	Rock characteristics
570.0-638.4	min mean max	23 76 97	2.8 4.4 6.2	3.86 7.59 18.72	66.1 99.0 153.4	medium compaction[1] quality from poor to very good[2] average and high strength[3] (571 to 577 m – poor quality, *RQD* = 23%) (600 to 607 m – poor quality, *RQD* = 44%)
638.4-775.0	min mean max	53 70 86	1.9 4.2 6.2	4.0 9.09 17.11	63.2 98.2 160.2	medium compaction[1] average and good quality[2] average and high strength[3]

* S – statistic parameters, *RQD* – rock quality designation index, f_d – Protodiakonow's rock compaction index, *n* – total porosity, R_c – compressive strength

[1] – according to Protodiakonow's classification, [2] – according to *RQD*, [3] – according to M. Borecki's rock mechanical classification, based on value R_c

Analysing the litho-stratigraphic profile of the exploration borehole, Duda (2005) points out that water-bearing layers in the sandstones of the Middle Buntsandstein (Table 3 & 4) are essential for determining the depth of rock mass freezing. They are medium-compact and fractured, interbedded with mudstones, claystones and shales. At a depth of 640.0-645.0 m sandstones have a very low hydraulic conductivity value. However, in the neighbouring S-373B borehole at depths of 574-635 m, a higher hydraulic conductivity of sandstones was determined $k = 7.3 \cdot 10^{-7}$ m/s (Dziedziak & Bielawski, 2005), which is indicative of a slightly higher permeability.

The interpretation of source data revealed that:

– unfavorable geomechanical conditions are observed in the area of Buntsandstein rocks due to the presence of numerous zones weakening the rock mass,

– deeper zones are recharged by a water leakage from upper, shallower aquifers through low permeable beds and hydraulic contacts in the crack zones that are accompanied by faults,
– in low-permeability beds the flow of groundwater is possible; this may result in piping failure and water inrush into the shaft, especially if water is under a hydrostatic pressure of several MPa.

When determining the rock mass freezing depth for shaft sinking, Duda (2005) focused on water-bearing layer at depths of 640-645 m. Assumption was made that in the event of insufficient freezing of the Middle Buntsandstein bottom zone, this layer may become activated. The water inflow may then result in faster melting of the lower part of frozen cover, intensifying the water inflow as a consequence. Therefore, a few metres of reserve thickness were added and finally the requisite rock mass freezing depth during the SW-4 shaft sinking was established for 650 m (Duda, 2005). The shaft sinking with the predetermined rock mass freezing depth was performed without failure, so the applied assessment criteria for the freezing were adequate.

4. Algorithm for determining rock mass freezing depth

Based on
– practical experience gained by the author while determining rock mass freezing depth in solid rocks under difficult hydrogeological and geomechanical conditions for sinking two shafts in LGOM,
– conclusions drawn from the history of shaft sinking in LGOM,
– assessment of factors and their effects influencing the determination of rock mass freezing depth for shaft sinking in solid rocks, including, among others, an analysis of factors and their impact on the uncertainty of source data obtained in the exploration boreholes and presented in geological reports,

a generalized algorithm can be suggested for determining rock mass freezing depth for shaft sinking in solid rocks under difficult geological conditions (Fig. 2). These conditions are also characterized by water pressure amounting to several MPa. The methodological algorithm and assumed values of assessment criteria are adequate especially for geological conditions existing in LGOM. Nevertheless, they can also be applied in other mining regions. The proposed algorithm quantitatively accounts for the influence of hydrogeological and geomechanical conditions occurring in water-bearing layers of solid rocks.

The aim of Stage 1 of the algorithm is to determine the depth range of water-bearing layers occurring in solid rocks, which will be the subject of further analysis. A detailed analysis (Stage 2) consists in examining if the assessment criteria are met by individual layers. The criteria include adopted threshold values of four parameters describing hydrogeological and geomechanical conditions: hydraulic conductivity (k), total porosity (n), rock quality designation index (RQD), Protodiakonow's rock compaction index (f_d).

Adopted threshold values, i.e. individual assessment criteria, are given as two values of a given parameter. They refer not only to the maximum value (for k and n) or minimum value (for RQD and f_d), but also to their mean values from the reports on geological research in exploration boreholes. This kind of flexible approach is necessitated by the need to account for the intrinsic variability of parameters in the rock mass, especially in a fractured one. Moreover, it is

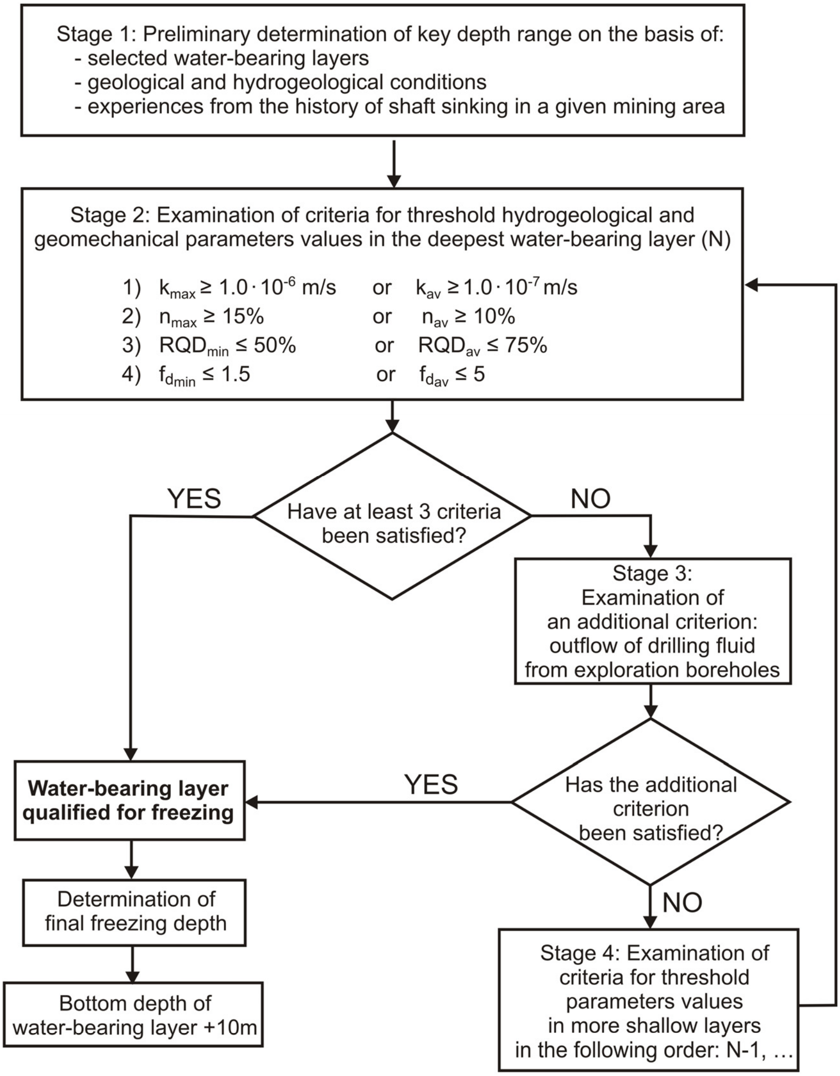

Fig. 2. Algorithm for the methodology of determining rock mass freezing depth for shaft sinking in solid rocks. *N* – number of the deepest water-bearing layer preselected for freezing, *av* – mean value, the rest of symbols were defined in the text

difficult to take rock samples from the same, narrow range of depths both for hydrogeological and geomechanical tests. It further increases the variability range of analyzed parameters referred to in the geological reports. It is, therefore, satisfactory to meet three analysis criteria in order to earmark a given layer for freezing.

If only two criteria describing a given water-bearing layer are met, an additional criterion (Stage 3) is examined to reduce the risk that the freezing depth was selected erroneously. The risk lies in the fact that the layer earmarked for freezing was not qualified. The occurrence of drilling fluid outflow in a studied borehole at a depth range corresponding to the assessed layer or its immediate vicinity is an additional criterion. If such a situation takes place, the assessed layer qualifies for freezing.

If the geological conditions in the deepest layer (marked as N) are favorable enough so that no freezing is necessary, one should proceed to Stage 4, i.e. examine assessment criteria in the successive shallow layers (N-1, N-2, …). This order of examination helps one to avoid the risk of skipping layers which need to be frozen. This is illustrated by a schematic example of a geological profile (Fig. 3). The profile includes four water-bearing layers selected at the stage of preliminary assessment. As a result of a detailed analysis carried out in accordance with the algorithm, each of the layers is checked out and a decision is made whether or not to freeze it. If a layer described as 4 is classified as not fit for freezing, layer 3 is assessed. Following the criteria adopted for this method, it is found out that freezing of layer 3 is necessary. Consequently, all layers located above it will be frozen as well.

When determining the requisite depth of rock mass freezing around the sunk shaft, a 10 m thick protective rock zone should be added to a bottom depth of the deepest water-bearing layer earmarked for freezing. Ultimately the final depth is obtained.

5. Conclusions

The algorithm for determining rock mass freezing depth for shaft sinking in water-bearing solid rocks under difficult hydrogeological and geotechnical conditions presented in this paper can be applied especially in LGOM. However, due to a more universal nature of the adopted assessment criteria, the methodology may be also used in other mining districts.

The presented approach can also be a framework for further research because it is possible to supplement the algorithm with other assessment criteria, especially in the case of considerable differences in geological conditions in other mining areas. It is also possible to modify it by providing different threshold values of assessment criteria. For example, adopted criteria may be tempered if the water pressure in water-bearing layers causing water hazard for shaft sinking is lower, e.g. 1-2 MPa.

For a better determination of rock mass freezing depth one should strive to take samples of a drill core with the purpose of carrying out strength tests from the same depth range, where rock permeability tests are performed.

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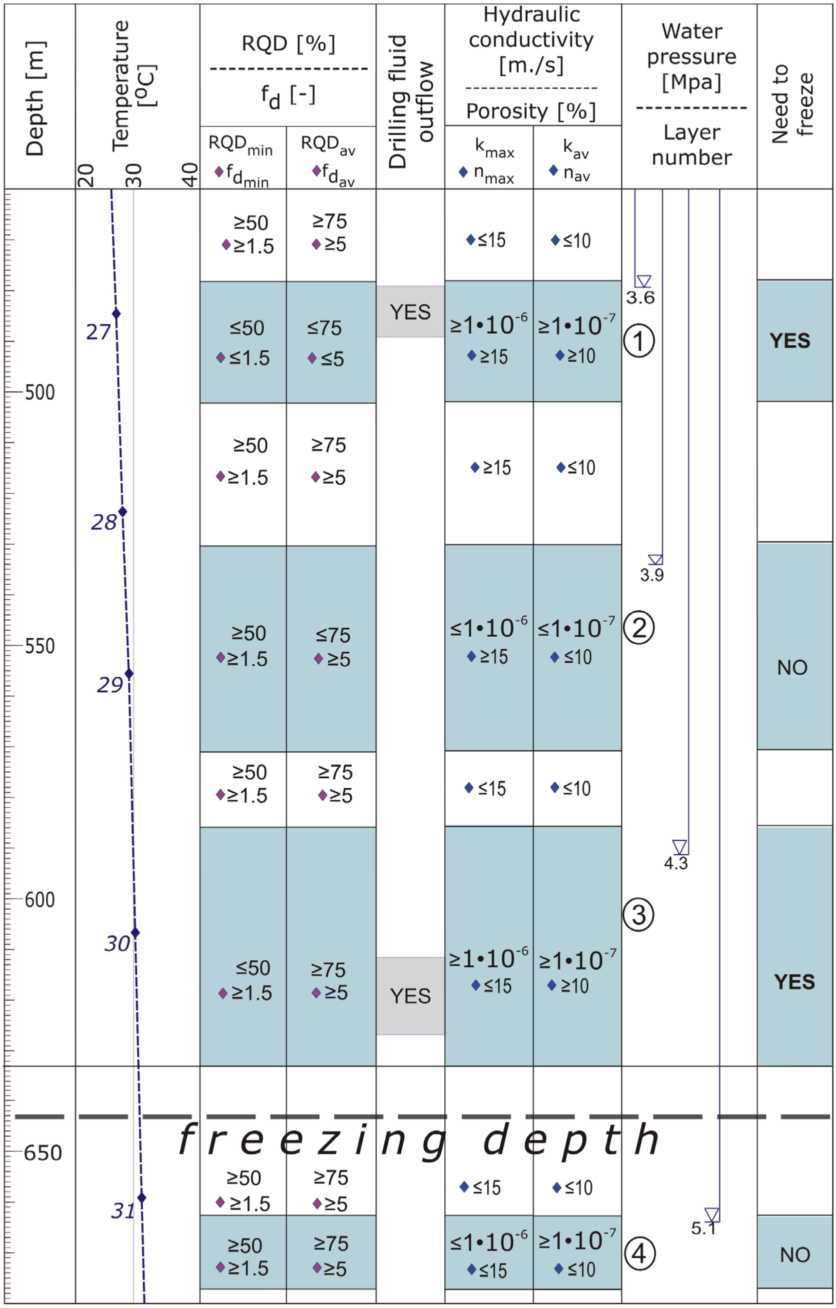

Fig. 3. Schematic profile illustrating the application of an algorithm for determining freezing depth (values of depth, temperature and water pressures are only examples)

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