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THE WATER STORAGE CAPACITY OF A CARBONIFEROUS ROCK MASS AND ITS IMPACT ON THE FLOODING PROCESS OF MINE WORKINGS IN THE UPPER SILESIAN COAL BASIN

CHŁONNOŚĆ WODNA GÓROTWORU KARBOŃSKIEGO I JEJ WPŁYW NA PRZEBIEG ZATAPIANIA WYROBISK GÓRNICZYCH KOPALŃ WĘGLA KAMIENNEGO W GZW

The water storage capacity of a rock mass as one of the factors flooding process affecting mines has not been thoroughly examined in the past. The value of the water storage capacity of rock mass has been obtained through field investigations and calculations, including the water capacity of the rock masses in the vicinity of mine workings and similar rock masses located beyond the mine workings themselves, but able to drain into the mined area.

In this paper, the so-called "additional" water capacity of rock masses in the external part of the drainage zone has been defined and a method for its quantification is presented. It allows to calculate the water storage capacity of a rock mass and the total void volume of the reservoirs. The water storage capacity of the Carboniferous rock mass in the Upper Silesian Coal Basin (USCB) has been estimated by using prognostic calculations and the results of field observations. It was estimated with respect to the complex geological and tectonic conditions and, in particular, to the hydro-geological and mining conditions, including the geo-mechanical properties of the rocks surrounding mine workings.

It has been found that the overall percentage proportion of each void volume- component's capacity in relation to the specific, empirically determined real volume of the reservoir can be proportionally responsible for its formation time and how the process develops. For capacities related to the water storage capacity of a rock mass, this proportion can be from 35% to 75%. Considering the wide use of the parameters in mines, the author also suggests using the so-called "rock-mass water-storage capacity index — d_{rm} in the calculations. This index can correct the total void volumes of the reservoirs in mine workings by introducing values of the water storage capacity of the rock mass and their local zones of drainage. The values of index d_{rm} for the reservoirs investigated can vary from 0.95 to 4.78. Knowing the principles of its determination, it may be used not only for the prediction of the flooding process in mine workings, but also for the prediction of the drainage process in flooded mine workings.

Key words: security, hydro-geology, rock mass, mine closure, process of flooding, methods of investigation

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Chłonność wodna górotworu jako jeden z czynników decydujących o przebiegu zatapiania kopalń nie była dotychczas szczegółowo badana. Ocena chłonności wodnej górotworu ograniczała się jak dotąd do określenia jej wpływu na proces zatapiania kopalń przy zastosowaniu tylko jednej z jej składowych, jaką jest pojemność wodna górotworu. W wyniku prac wykonywanych w GIG w aspekcie zatapiania likwidowanych kopalń w latach 1994–1997 stwierdzono, że uzyskana na podstawie obliczeń i badań polowych wartość chłonności obejmuje pojemności wodne zdrenowanego górotworu objętego zasięgiem występowania wyrobisk górniczych oraz górotworu w zasięgu odwodnienia, lecz położonego poza zasięgiem wyrobisk górniczych (rys. 1). Jest ona ponadto wartością korygującą dla znanych sposobów obliczeń pojemności wodnej wyrobisk górniczych, szczelin poeksploatacyjnych (rys. 2) i górotworu (pojemności intergranularnej skał) dla podziemnych zbiorników wodnych (Rogoż 1978; Konstantynowicz i in. 1974; Bukowski 1999, 1999a).

W niniejszej pracy zdefiniowano tzw. pojemność dodatkową i przedstawiono sposób jej wyznaczania (wzór 3), a tym samym wyznaczania chłonności wodnej górotworu i całkowitej pojemności wodnej podziemnych zbiorników (wzory 1–5). Dokonano podziału wód gromadzonych w tych zbiornikach na składowe pojemnościowe (tabl. 1). W oparciu o podstawy teoretyczne i badania własne autora określono warunki, jakim powinny odpowiadać podziemne zbiorniki obserwowane w kopalniach węgla kamiennego w GZW (rys. 3). Wyniki obserwacji zbiorników spełniających te warunki posłużyły do wyznaczenia parametrów określających chłonność wodną górotworu oraz dla charakterystyki składowych pojemnościowych (rys. 5). Określając warunki obserwacji zbiorników na potrzeby oceny chłonności przedstawiono również podstawy geometryczne obliczania pojemności wodnej górotworu i części szczelin poeksploatacyjnych, które mogą zostać wypełnione wodą (rys. 4). Omówiono wpływ chłonności wodnej górotworu na przebieg procesu zatapiania wyrobisk górniczych i ich naturalnego otoczenia. Posługując się wynikami obliczeń prognostycznych i wynikami obserwacji polowych, w nawiązaniu do złożoności warunków geologicznych i tektoniki, a szczególnie warunków hydrogeologicznych oraz warunków górniczych, zwłaszcza własności fizykomechanicznych skał otaczających zatapiane wyrobiska górnicze, dokonano oceny chłonności wodnej górotworu karbońskiego w GZW. Pomimo tzw. „typowego" przebiegu procesu zatapiania zrobów, charakteryzującego się dłuższym od prognozowanego czasem zatapiania, stwierdzono wyraźne różnicowanie czynników decydujących o zachodzeniu tego procesu (rys. 6, 7).

Określenie wszystkich składowych pojemnościowych umożliwiło uzyskanie pełnego obrazu struktury tworzonego zbiornika wodnego (rys. 5) i wpływu jego poszczególnych składowych, związanych z chłonnością wodną górotworu lub procesem eksploatacji, na przebieg zatapiania (rys. 8). Stwierdzono, że ogólny udział procentowy każdej z tych składowych w stosunku do określonej empirycznie pojemności rzeczywistej zbiornika odpowiada proporcjonalnie za czas i przebieg jego formowania się. Dla pojemności związanych z chłonnością wodną górotworu udział ten waha się od 35 do 75% (rys. 8). W znacznym uproszczeniu można stwierdzić, że stosunek chłonności wodnej górotworu do pojemności wyrobisk górniczych i szczelin poeksploatacyjnych w różnych rejonach GZW i w zróżnicowanych warunkach występowania zbiorników wodnych nie ulega poważniejszym zmianom, lecz w obrębie pojemności składowych chłonności wodnej górotworu zmienia się stosunek objętościowy wód intergranularnych do szczelinowych.

W aspekcie szerokiego zastosowania w kopalniach, obok innych parametrów, autor proponuje wykorzystanie w obliczeniach tzw. „wskaźnika chłonności wodnej górotworu". Wskaźnik ten koryguje całkowite pojemności podziemnych zbiorników wodnych powstałych w wyrobiskach górniczych o chłonność wodną górotworu w obrębie lokalnego dla zbiornika leja depresji. Jest on stosunkiem rzeczywistej pojemności zbiornika uzyskanej empirycznie (V) do łącznej pojemności wolnych przestrzeni obliczonej dla zrobów i wyrobisk korytarzowych ($V_z + V_k$) — oznaczony jako d_{ch} (wzór 6), rzadziej z uwzględnieniem pojemności szczelin i spękań poeksploatacyjnych, wówczas oznaczony jako D_{ch}. Wartości wskaźnika d_{ch} określone dla zbadanych zbiorników wodnych zmieniają się w zakresie od 0,95 do 4,78 (rys. 9). Parametr ten, przy znajomości zasad jego wyznaczania, umożliwia korygowanie całkowitych pojemności zbiorników wód podziemnych w kopalniach i powinien pozwolić na obniżenie błędu prognozowania procesu zatapiania nawet o około 50%. Może znaleźć szerokie zastosowanie praktyczne nie tylko w prognozowaniu zatapiania, lecz także w prognozowaniu procesu odwadniania wyrobisk górniczych.

Słowa kluczowe: bezpieczeństwo, hydrogeologia, górotwór, likwidacja, zatapianie, metoda badań

1. Introduction

From the point of view of hydrodynamic events the final result of the prediction of the flooding process for mine workings in an abandoned mine will be an estimate of the groundwater table recovery time in the mine workings and the surrounding rock masses. This time can only be estimated after the drained void space of the mine and the predicted groundwater level changes have been calculated and after the water balance and a predicted value of the inflow rate into the part of the mine to be flooded are estimated.

The mining-related drained void spaces directly result from the applied mining method and the way the mine is abandoned. It can be separately characterized by the empirically determined coefficient of water capacity of the goaf *"c"* for the room-and-pillar and longwall mining and post-mining rock's fracturing. It depends on the mining using different types of filling material and the way of backfilling (Rogoż 1978). This coefficient can not be applied to estimate the total void volumes of the passageways. Among the void spaces in rock mass created by mining, only estimations of the residual — goaf voids for the Upper Silesian Coal Basin (USCB) mines could be obtained with accuracy within acceptable limits. The calculations made for the void volumes describe the so-called storage capacity of the rock masses — for rock masses surrounding the mine workings are far from ideal and homogenous (Bukowski 1999). The improvement in accuracy has recently been made possible due, among other factors, to the development of a technique for determining the coefficient of the gravity drainage capacity (Bukowski 1999, 2001). This coefficient can be used to evaluate the maximum value of the rock's gravity drainage index (Wilk and Szwabowicz 1965) the determination of which, for technical reasons, might particullary be difficult to obtain.

In the prognostic calculations, the water capacity of rock masses situated within the cone of depression defined by the volume of water stored by the overburden rock porosities within mining areas has been taken into account. The water capacity of the rock masses may often be confused with the water storage capacity of the rock mass. For a long time, this has been thought to be one of the most important causes of calculation error, directly influencing the accuracy of prediction of the flooding of mine workings, as many authors have pointed out (Rogoż and Posyłek 1993; Rogoż et al. 1995; Vaselič and Norton 1997). According to Vaselič and Norton (1997), of the total prediction error related to the computation model, component determination errors may be up to the order of several hundred percent. In the opinion of most authors addressing the prediction of the mine flooding process, the correct calculation of the void volume in considered difficult and a calculation error is often a result of difficulties in estimating the volume of drained rock masses. Estimations have involved many calculation reductions and simplifications, mainly as a result of the inability to obtain necessary output data. In particular, in the numerical modelling, the additional void volume possibilities of the rock masses or the aquifer adjacent to mining panels, within the extent of their drainage zone (that can be associated with the water storage capacity of rock mass) have been neglected (Bukowski, 2000). Thus, the substantial discrepancies between the calculated figures for the flooding time of mine workings and the amount of water stored in them, in comparison with direct observations, have stimulated the author to undertake the task of examining the problem of estimating the water storage capacity of the rock mass. In these considerations, the problem of variable water inflow to the mine during flooding, which has been the subject of earlier papers (Rogoż 1994; Vaselič and Norton 1997, Cempiel 1999) has been set aside. Instead, the author has focused on finding, as accurately as possible, a definition of the impact of the total available void volume on the water reservoir formation process in the flooding of mine workings in the USCB area.

2. Water storage capacity of a rock masses as a subject of hydro-geological studies

The water storage capacity of rock masses has been studied for many years but only in connection with the process of injecting water, waste and other fluids into flooding-prone rocks. The water storage capacity of rock masses determined in-situ could be defined as the specific or unit water storage capacity and refers to any rock void space associated with both the porosity of rocks and fracturing of the rock mass. That definition, essentially, could not refer to the strata surrounding the abandoned mine workings due to its different, forced nature. The specific water storage capacity has been studied during the process of fluid injection into the rock masses. It can be applied chiefly to the subsoil imperviousness assessment in hydro-technical structural projects, to designing geothermal energy installations in southern and north-western Poland and to injection of liquid wastes and consumed waters as a ballneologycal and geothermal wastes. The feasibility of the permanent or circulating discharge of brines into un-mined areas of rock has also been studied for a long time (Rogoż 1992; Różkowski et al. 1995; Rogoż and Posyłek 2000).

As a result of studies on the water storage capacity of rock mass with respect to the flooding of abandoned mines carried out by the Central Mining Institute (GIG) from 1994 to 1997, the value of water storage capacity of rock mass was found. It was obtained from field studies and calculations, including the capacities of rock masses in internal part of the drainage zone and the drained rock masses located beyond the mine workings. Furthermore, this can also constitute a correcting value for the water capacity of the goaf and post-mine rock fracturing in calculating water reservoirs (Bukowski 1999, 2000). These findings were based, among others, on the results of studies carried out by Rogoż (1978), Konstantynowicz et al. (1974), and Kotyrba (1993) on the water capacity of goaf to be filled with inflowing water with respect to the extent of post-mining rock fracturing. It should be noted that, to date, there has been no requirement for a definition of the water storage capacity of a rock mass for strata surrounding operational mine workings in the USCB area; the visible lack of studies on this subject can be interpreted as evidence of the dearth of problems. Specially-created underground mine-water collection reservoirs were only considered exceptionally as being places to store saline mine-water (Wilk et al. 1988; Adamczyk et al. 1992; Szczepański et al. 1993). The possible accumulation of highly mineralized water in old mine workings in the USCB has only been analysed for a portion of the goaf in the "Silesia" coal mine. From the approximate output data on the hydro-geological properties of the rock applied for the modeling studies, the authors have determined the amount of brine that may be stored in a part of this mine's goaf.

The studies currently conducted on the water storage capacity of a rock mass have chiefly related to its void volume connected with rock's porosity (water capacity of rock masses). They were conducted, especially to the prediction of water inflow to the mine workings, in the newly developed parts of the mineral deposit. In this paper, the concepts of water capacity of rock masses (void volume of rock masses overlying the mine workings) and water storage capacity of a rock masses are considered as separate terms, with an attempt to define the latter.

Conceptually, the water capacity of rock masses can refer to the water bearing stratum or aquifer, and its ability to store water. The aquifer void volume (V_r) can simply be defined as a ratio of the drained or stored water as a result of the aquifer's water-table fluctuation to the water bearing rock volume (Kleczkowski and Różkowski 1997). According to this definition, the aquifer void volume — water capacity of rock masses, particularly in strata with a free water table, can be close to the value of the storage coefficient and can be used in the case of an extensive continuum with properties resembling those of isotropic medium. The concept of the aquifer void volume has been reported in many papers concerning mine flooding (Rogoż and Posyłek 1993, 1998; Rogoż et al. 1995), although to emphasize the rock saturation process, it could be referred to as "the rocks absorbability" (Fiszer 1995).

On conducted observations and numerous prognostic calculations for the USCB mining areas being abandoned, it has been found that the aquifer void volume (water capacity of rock masses — V_r) might be highly in excess of the water capacity of the goaf and passageway void volumes. The water capacity of the rock masses, as expressed above, and according to the author, can principally be related to the drained rocks' water storage capacity or their ability to collect and store water in areas of underground mining. It should be considered as one of the components of the water storage capacity of the rock mass (Fig. 1). This ability, in connection with overlying rocks, can be considered as the water capacity of the rock mass within the cone of depression — drainage zone (V_r : mainly related to the gravity drainage capacity of rocks) and for the strata lying within the rock drainage and mine-water recovery zones.

But in regions external to the mine workings the water-storage capacity is currently taken into consideration as the so-called "additional water capacity of the rock mass" (V_a) (Bukowski 1999, 2000). Its importance to the mine flooding process and, first of all, to the nature and variability of the additional water capacity of rock masses related to the external part of the cone of depression (external part of drainage zone) may be considerable. It is proposed to isolate this external portion and to call it "additional capacity" (V_a). Its value can involve not only the inter-granular porosity of the rock but also the partial void volume of the naturally occurring fissures connected with the network of mine workings. The latter is difficult to estimate. Fissures may be of different extent, because their size is affected in areas of mine workings and is proportional to the proximity to them.

The additional capacity should be linked to the strata lying between mine workings up to the outer boundary of the cone of depression or drainage zone (majority part of coal mines in the USCB formed regional cone of depression). The additional capacity (in the external part of the drainage zone — V_a) related to the horizontal ground-water flow due to the flooding of the mine can vary. It depends on several factors, especially geological, and may significantly exceed the overburden water capacity of the rock mass in the internal part of the drainage zone (V_r) (Fig. 1).

Hence the water storage capacity of a rock mass in areas disturbed by mining and located within the mining impact zone implies the ability of the rock mass body affected by drainage to store a certain amount of water during the process of flooding, as well as groundwater recovery. This ability is related to the presence of natural rock pores and fissures within and beyond the reach of mining activities and to a small extent to post-mining rock fracture of inconsiderable horizontal spread.

It is important to note that using the existing means of calculations of water capacity, especially in case of longwall mining with controlled roof collapse, for the strata within and overlying the mine workings it is assumed that the rock mass structure is very extensively disturbed. The classical concept of the water capacity of rock masses no

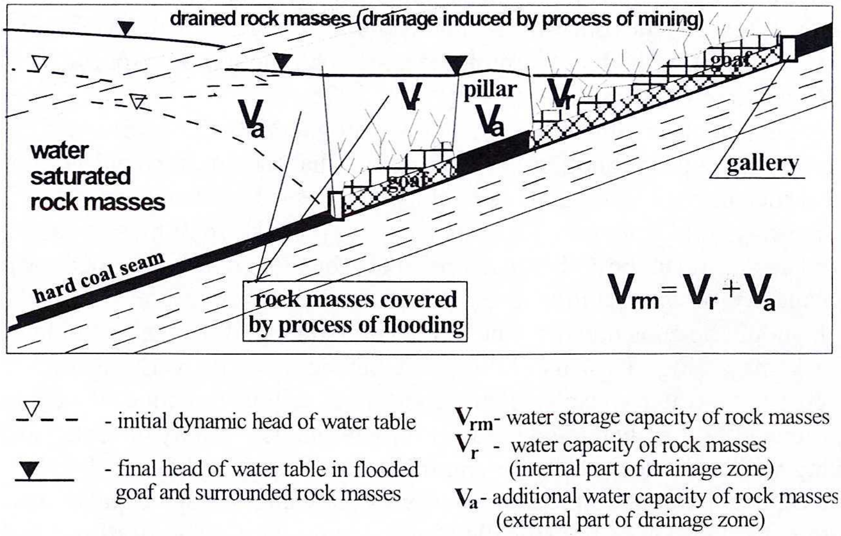

Fig. 1. Schematic hydro-geological cross-section showing the water reservoirs' partially void volumes, which define the water storage capacity of a rock masses

Rys. 1. Schematyczny przekrój hydrogeologiczny ilustrujący składowe całkowitej pojemności zbiornika określające chłonność wodną górotworu longer applies, since the water capacity is now connected with natural porosity of the fractured rock mass. Therefore, in the calculations, the storage coefficient of gravity water defining solely the free water content in rock pores (Bukowski 1999, 2001) or the gravity drainage index — temporal free water content (Wilk, Szwabowicz 1965) are used. The water capacity of the post-mining fractures of roof-strata overlying the mining area (goaf) are separately estimated.

3. Partial void volumes and classification of minewater collected in underground reservoirs formed in abandoned mine workings

The formation of water reservoirs in mine workings planned for partial or total closure can form a final phase of the closure, since it is an inevitable natural process. Also, flooding of mine workings in active mines is not an unusual phenomenon, resulting in the formation, on average, from a dozen or so to more than a hundred underground water-filled reservoirs of different size (from several hundred to several hundred thousand m^3) in each mine. These water reservoirs have been formed as a result of drainage into different mining systems and where different mine closure techniques

TABLE 1

Partially void volumes of underground water reservoirs formed in mining excavations

TABLICA 1

Składowe pojemnościowe zbiorników utworzonych w wyrobiskach górniczych

Kinds of void volume with respect to the manner of void space formation	Water inflow rate	Kinds of capacity — kinds of void volume	Notation
V_m = volume of void spaces formed directly related to processes of mining	Waters of high inflow rate	Water capacity of the goaf	V_g
		Water capacity of the passageways	V_p
		Water capacity of the post-mine rock fracturing	V_f
		$V_m = V_g + V_p + V_f$ (relation 1)	
V_{rm} = volume of void spaces formed indirectly related to mining and rock drainage Void volumes related to water storage capacity of rock mass	Waters of relatively low inflow rate	Water capacity of rock masses in internal part of drainage zone, including overburden rocks' inter-granular free spaces (water obtained by coefficient of gravity drainage capacity or gravity drainage index and volume of rock masses)	V_r
		Water capacity of rock masses in external part of drainage zone, including drained rock masses of the peripheral parts of the cone of depression so-called as additional water capacity of rock masses	V_a
		$V_{rm} = V_r + V_a$ (relation 2)	

have been applied, due to the closure of mining areas due to the removal of all exploitable coal reserves. The total void volume of the reservoirs comprises of all partial void volumes; those directly formed as a result of mining operations and those free spaces which were initiated by the process and formed as a result of drainage of the rock masses (Table 1).

The void volumes directly resulting from mining operations (V_m) are identified as follows: goaf (V_g), passageways (V_p) and post-mining rock fracture (V_f) as shown in Fig. 2. These void volumes, expressed by water-capacity volumes have also been defined as the amount of water involved in (Table 1) the high rate flow that takes place in the void space during the initial phase of draining or flooding (Bukowski 1999, 2000).

Principles of calculation of each kind of void volume are directly related to the type of mining and the total water capacity of rock masses of the USCB hard coal mines, including mining and geological conditions. It has been described many times in the past (Rogoż 1978; Rogoż and Posyłek 2000).

In general, it should be noted that the void volumes directly related to mining (V_m) are the sum of the above-mentioned partial void volumes, as defined by expression 3.1 (Table 1). The value of each total void volume depends, first of all, on the mining system and the method of excavation removal. Only the total void volume of passageways can, to some degree, be linked to the mine structure and the extent of face line advance and the distribution of such faces within the mine associated with. Its contribution to the total void volumes directly related to mining can increase significantly with depth, compared with the void volume of the goaf. This results from the behaviour of mine workings at greater depths and largely from the great intensity difference in the clamp processes for goaf described with the reduction ratio variability (coefficient of water capacity of the

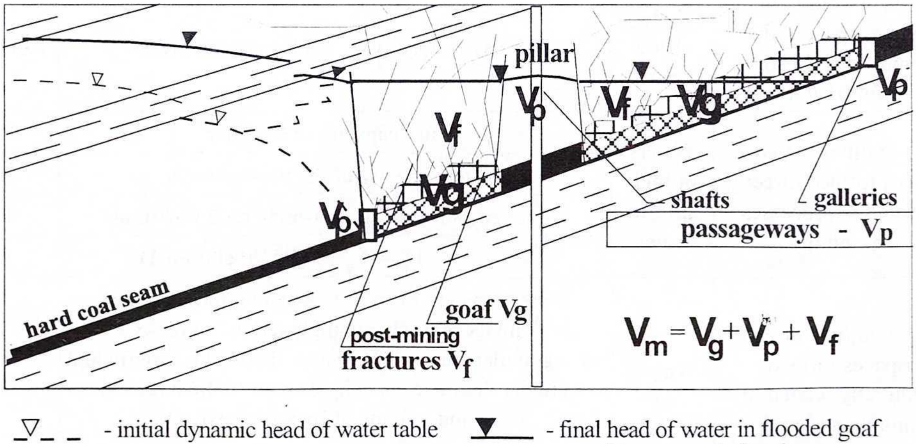

Fig. 2. Partially void volumes of underground water reservoirs formed in mining excavations directly related to process of mining

Rys. 2. Składowe pojemnościowe podziemnych zbiorników wodnych powstałych w wyrobiskach górniczych wynikające bezpośrednio z procesu eksploatacji goaf "*c*" — Rogoż 1978). The passageways, especially driven at depths greater than 800 m surrounded by competent sandstone strata are not clamping so intensive as goaf (Kidybiński 1982).

While the total void volume of the goaf and passageways of the USCB hard coal mines can easily be determined (coefficient "*c*" Rogoż 1978), the estimation of the post-mine rock fracturing extent is unusually difficult. This applies particularly to mines being abandoned, where taking direct measurements is often impossible. In the case of large areas, mostly already inaccessible, it is necessary to obtain an estimated value of the total void volume of the post-mining rock fractures and fissures. Such an estimate is principally obtained by comparing the surface subsidence trough volume caused by the exploitation of a given seam but only when the mining coefficient ("*a*") and the reduction ratio ("*c*") are known (Rogoż 1978). From the results of observations carried out in mines of the USCB, according to Konstantynowicz et al. (1974) it can be assumed that the majority of post-mining fractured rocks are able to store water, then being concentrated above the seam in layers up to around 15 times the seam thickness. It is impossible to obtain a separate estimate of the void volumes of the natural and mining-deformed rock fissures, particularly in shallow mines, without taking measurements in mine workings and outcrops.

The capacities of rock masses in the internal part of the drainage zone (water capacity of the rocks V_r) (section 2) and of the peripheral part of the cone of depression related to the additional capacity (V_a), defined above, should be considered as void volumes (capacities) indirectly related to mining. The sum of these two void volumes, which can be assessed and expressed in terms of a water volume (relation 2, Table 1) constitutes a void volume defining the water storage capacity of the rock mass. The reservoir's water related to the water storage capacity of rock mass was conventionally defined as the water with a slow flow-rate that seeps over a long period of time in comparison with the time taken the drain the goaf (Bukowski 1999, Table 1). The water storage capacity of the rock mass corresponds, more or less, to the total void volume of the drained rock masses or aquifer (Vaselič and Norton 1997).

The water capacity of the rock masses in the external part of cone of depression is the difference between the volume of water actually used to form a reservoir in the goaf (V), for example measured by water-meter and the theoretical volume of water in the reservoir — V_c (Bukowski 1999):

$$V_a = V - V_c \tag{3}$$

The actual total void volume of the reservoir formed in the abandoned mine workings (V), which should theoretically correspond to the predicted volume (V_c), has_been hitherto determined as the sum of the mining void volume (V_m) and the free spaces in the rock mass (intergranular spaces in rocks — V_r):

$$V_c = V_m + V_r \tag{4}$$

The water capacity of the rock masses within the cone of depression is calculated on the basis of the volume of the rocks or their proportional share of the whole, in a vertical profile using a value of the storage coefficient or gravity drainage index. This quantity is often insignificantly small hence the principal cause of discrepancies in the calculations, to what has been defined as the additional capacity. The latter value, which is chiefly related to the natural and secondary fracturing of the rock masses, can be crucial for the assessment of their water storage capacity and thus for the assessment of the total void volume of a reservoir.

According to the obtained estimate of the partial void volumes of underground water reservoirs that are forming, their actual total void volume (V), (relation 4) should be expressed as:

$$V_c = V_m + V_{rm} \tag{5}$$

It follows that the calculated total void volume of a water reservoir (V_c) will only conform to its real total void volume (V) when the void volumes related to the water storage capacity of rock mass (sum of V_r and V_a) are accurately estimated and taken into account overall. The estimation error of the water volume in the reservoir and the mine flooding time prediction error, largely depend on these.

4. Prediction of the mine flooding process and the conditions and criteria for obtaining an accurate estimate of the water storage capacity of a rock mass

The partial void volumes of the underground water reservoirs given above were calculated for various geological, hydro-geological and underground mining conditions and were considered individually in the assessment of their impact on the process of mine flooding. The most recently, widely used method is a prediction method partially or totally based on numerical methods. The numerical modelling and prediction of the flooding process of abandoned mine workings is often based on authoritative computer programs and software firms programs (Rogoż 1994; Sherwood and Younger 1994; Fiszer 1995; Szczepański et al. 1998) which are commonly used to modelling of the aquifer.

Some authors of such computer-based solutions have often stated that for the USCB mines a method allowing multi-variant calculations is the most appropriate. It should be noted that numerical modelling of this process requires substantial simplification when developing a model and is not useful understanding the nature of voids in rock masses. It could be acceptable were there no possibility of the occurrence of water hazards in active mine workings and at the surface. The purely theoretical modelling method allows mathematical manipulation without taking into account the actual physical reality (model calibration procedure). The verification of multi-variant prognostic calculations by means of in-situ measurements of the progress of flooding permits rapid modification of the prognosis (Bukowski 2000). In general, without a detailed analysis of the total void volume of the mine workings and rock mass or aquifer it is not possible to account for the water storage capacity of a rock mass in numerical modelling. According to the majority of researchers, in addition to the inflow assessment errors, this could be one of the causes of significant discrepancies between the predicted course of events and subsequent observations of the process in reality.

To properly determine the water storage capacity of a rock mass and to take it into account in predictions, specific conditions and criteria must be met. In order to do so the author selected a number of test sites. The conditions that should be met by such water reservoirs to enable the assessment of the water storage capacity of a rock mass are as follows:

- the possibility to monitor the water table height variations during the formation of the reservoir, or the possibility to measure initial and final water table heights and the time of water recovery,
- the ability to detect when the reservoir was filled and was beginning to drain into the surrounding area when direct observations were not practicable,
- calculation of the water balance and monitoring the stability and rate of water inflow to the flooding-prone part of the goaf and obtaining a value for the water inflow thereto as accurately as possible,
- the possibility to assess the water-saturation state of the mine workings immediately prior to the start of flooding — an assessment of the extent of the existing water reservoirs,
- in the case of uncontrolled water infiltration from the water reservoir entering adjacent mine workings, as, for instance, through the boundary and barrier pillars, measurements of the variability and rate of this discharge or, at least, estimations of the scale of this process should be possible,
- the possibility of goaf flooding using salt mine-water or brine and mine workings self-flooding using natural water discharge should be done only in the areas where the fly ash or the other waste material to backfilling of mine workings is not used,
- the possibility to assess geological and hydro-geological conditions and the properties of the rock voids as well as the possibility to estimate the volume or proportion of the rocks able to store water,
- the possibility to obtain data and information about earlier mining and on the current conditions influencing the behaviour of the goaf and the surrounding rock mass,
- the possibility to evaluate the basic physico-mechanical parameters of rocks and the quality of the rock mass immediately overlying the extracted seam,
- the possibility to obtain a petrographic evaluation of the water-storage prone strata within the planned hydraulic head reach of the reservoir and also to distinguish strata prone to swelling,
- knowledge of the mining coefficient ("*a*") within a given part of the deposit,
- knowledge of the degree of filling inside of disposal shafts and degree of clamp of galleries and the other mine workings.

It have to be noted that the water reservoirs in the majority of mines exist within the regional cone of depression formed during decades of mining activity in the USCB area. The majority of the above data should be available from geological and mine surveying departments and some data may be obtained from the mine seam maps and the geological profiles and cross-sections. On analysing the water storage capacity of the rock mass under stable hydro-geological conditions, individual underground water reservoirs formed in mine workings, with known or continuously measured inflows and with negligible variation in water table were taken into account. Thus, an attempt was made to exclude the impact of variability in the cone of depression (drainage zone) on the discharge rate and volume calculations.

During partial mine flooding, only the portion of water-table capacity due to rock-fractures below the predicted water table was taken into account. Similarly, the volume of rock masses involved in the flooding process was determined for the purpose of calculating their void volume (Bukowski 1999,1999a, 2000).

5. The water storage capacity of the rock mass: in-situ studies

In this paper an attempt is made to obtain a complex solution of the problem. It is proved the thesis states that the dynamics of mine flooding process depends largely on the water storage capacity of the rock mass. This capacity may be determined through either direct measurement of goaf flooding or through prognoses. The paper presents the parameters determining the water storage capacity of a rock mass and some their numerical values obtained.

5.1. General characteristic of the conditions of formation of a water reservoirs

To determine the effect of the water storage capacity of the rock mass on the mine flooding process, the data on the goaf water reservoir formation obtained were analysed. The data were from the following mines (Fig. 3): Jan Kanty (under closure), Morcinek (closed); Silesia, Anna, Marcel, Pokój — section Ruch Wawel (closed), Concordia (closed) — Pstrowski mining area (under closure), Karol (closed) — Centrum-Szombierki mining area (under closure), Maria (closed) in Grodziec mining area (closed).

The water reservoirs observed are located within the Łaziska, Orzesze and Ruda Series, each comprising one reservoir, and within the Poręba and Jaklowice Series, each comprising three reservoirs. Among the reservoirs, only those of the Saddle Series could not be included in the in-situ studies. Due to the difficulties in obtaining data and the relatively small number of test sites, it was impossible to correlate the variability of results of the studies with a depth in coal mines performed in each Series of the Carboniferous rock mass.

The shallowest (< 200 m) water reservoir is located in the abandoned Maria coal mine, in coal seams No. 615, 616, 620, 621 and 622 mined by the shortwall system, the country rock of which is composed of only 30% of low porosity sandstone. The remaining water reservoirs, observed within the Coal Measure's Marginal Beds, are located at depths from 570 to 1050 m. That are as follows:

- The reservoir at 540 m in the caving and back-filling-induced goaf, following the extraction of seams No. 615 and 620 with a seam thickness of about 1.5 m in most

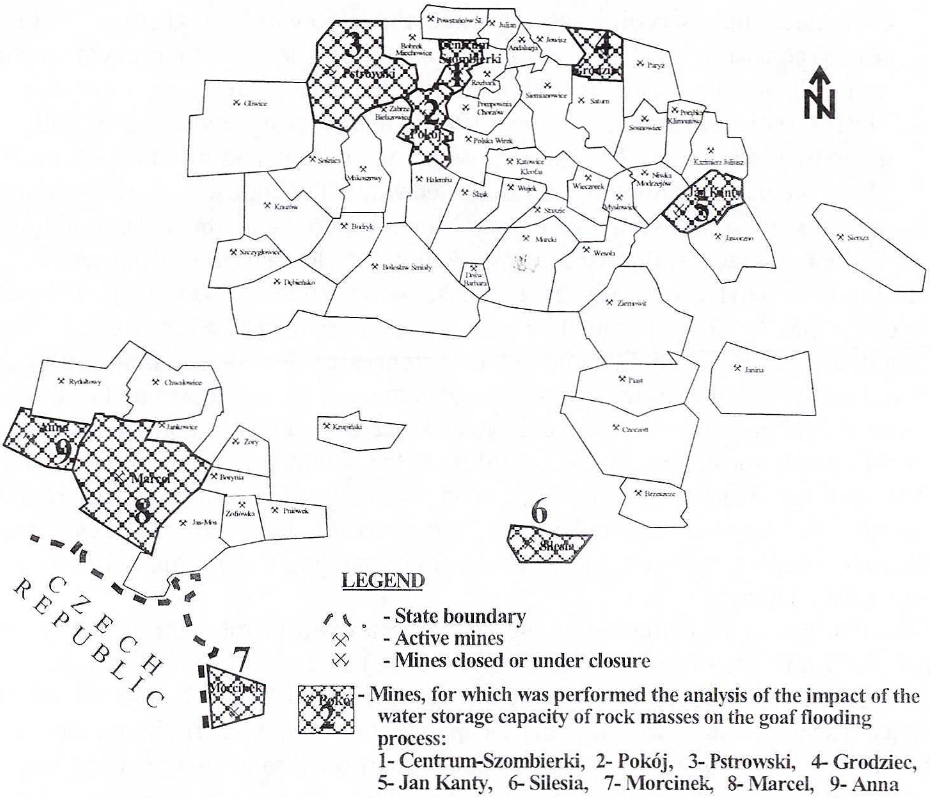

Fig. 3. Sketch map of the mining area in the Upper Silesian Coal Basin (USCB)

Rys. 3. Szkic sytuacyjny obszarów kopalń w Górnośląskim Zagłębiu Węglowym (GZW)

areas of the closed Centrum-Szombierki coal mine. This reservoir is located within the Poręba Series (group 600 of coal seams) consisting of about 40% of sandstones with a distinct, local and regional disjunctive tectonic setting.

- The reservoir at a depth of 570 m in the caving-induced goaf, following the extraction of seam No. 705 with a seam thickness of about 1.0 m in the "Concordia small fold" of the closed Concordia coal mine. This reservoir is located within the Jaklowice Series (group 700 of coal seams); strong beds consisting of about 20% sandstones.
- The reservoir at a depth of 630 m in the caving-induced goaf, following the extraction of seam No. 613 with a seam thickness of about 1.5 m in the Pokój coal mine. This reservoir is located within the Poręba Series (group 600 of coal seams) consisting of 100% sandstone (up to the planned water table) with distinct, small, disjunctive tectonics within the flooded part of the seam.
- The reservoir at a depth of 850 m in the caving-induced goaf, following the extraction of seam No. 707/1-2 with a seam thickness of about 4.2 m in the Anna

coal mine. This reservoir is located within the Jaklowice Series (group 700 of coal seams) consisting of 31% sandstones (up to the planned water table) with distinct, small, disjunctive tectonics within the flooded part of the seam.

- The reservoir at an average depth of 1000 m in the caving-induced goaf, following the extraction of seam No. 707/1-2 with a seam thickness of about 4.2 m in the Marcel coal mine. This reservoir is located within the Jaklowice Series (group 700 of coal seams) consisting of 71% sandstones (up to the planned water table) with distinct, heavy, disjunctive tectonics within the flooded part of the seam.

Strata adjacent to the reservoirs are composed of strong rocks; stronger than the other rocks of the USCB. They are mostly sandstones of more than 90 MPa strength. Within the flooded parts of the goaf, numerous occurrences of discontinuous tectonics were observed along with the strata dipping at angles ranging from 5 to 25° and in the Anna and Marcel coal mine areas showed evidence of increased methane content. The head of water inflow into the old workings, according to the volumetric calculations, varied for each reservoir from around 14 m to around 66 m with the inflow rate varying from 0,04 to 4,0 m^3/min. The reservoirs under study, formed within the Coal Measures Marginal Beds, have a typical individual total void volume ranging from around 19 000 m^3 to around 1 800 000 m^3.

Observations and calculation studies were performed in the Morcinek coal mine within the Ruda Series (group 400 of coal seams) at a depth of 1050 m on a fire-protection caving goaf reservoir formed in seams No.406/1, 406/2, 404/3-4, 404/1-2. These coal seams were extracted with a seam thickness of up to 4.2 m in mine workings with a water head of about 50 m. The average proportion of sandstones was estimated to be about 30%. Within the strata adjacent to the old flooded mine workings and showing angles of dip up to 15°, a number of rock fracturing and dislocation zones, as well as an increased methane content were observed. A water meter installed in the fire protection pipeline indicated a mean discharge rate of 2.43 m^3/min and a total of about 142 000 m^3 of water discharged into the mine workings.

Within the Orzesze Series (group 300 of coal seams), reliable monitoring of the water table and inflow variations was undertaken in the Jan Kanty coal mine in a water reservoir formed in caving-induced goaf of seam No. 304/2. This coal seam has been exploited with a seam thickness of about 2.85 m and at a depth of about 350 m. Calculations and monitoring of the flooding process was only be possible a height intervals of the order of several meters. It took place inside an impervious clayey strata of weakly developed discontinuous tectonics dipping monoclinically at an angle not exceeding 10°. The rocks contained minerals prone to swelling and showed low strength and high strain values. The total void volume of the reservoir, amounting to about 50 000 m^3, filled up with water over a short time at an inflow rate of about 3.3 m^3/min.

Within the Łaziska Series (group 200 of coal seams), the observation and calculation studies were undertaken on a reservoir formed in the Silesia coal mine within the framework of the program of reducing mine-water discharge onto surface receiver sites. The controlled level of water was collected in the caving induced goaf of seam No. 214/1-2. This seam was exploited with a seam thickness of 3.2 m at a depth of about

500 m. The geological environment of the water reservoir showed relatively low tectonic influence (weakly developed disjunctive tectonics, angle of dip — up to 15°) and a proportion of 85% of sandstones. These sandstones were characterised by high open porosity, high gravity drainage capacity, permeability, and low compressive strength. Among the clayey rocks and the clay binder sandstones, accumulations of minerals prone to swelling were found. Brine at a mean inflow rate of about 1.29 m^3/min was discharged into the workings, of which about 450 000 m^3 has been stored within a 35 m head of water exchange. Within this reservoir, during its formation, five calculation intervals, for which the process of the water-rising was considered, have been resolved.

To calculate the water capacity of rock masses and to estimate the water capacity of post-mine rock fracturing available to contain the water, geometrical models based on the principles of a solid body volume calculation (Bukowski 1999, 1999a) and accounting for the spatial layout of mine workings were used. In general, the two following geometrical models were assumed:

- pyramid for the Pokój (Wawel) coal mine,
- half and full rectangular parallelepipeds for the remaining water reservoirs (Fig. 4).

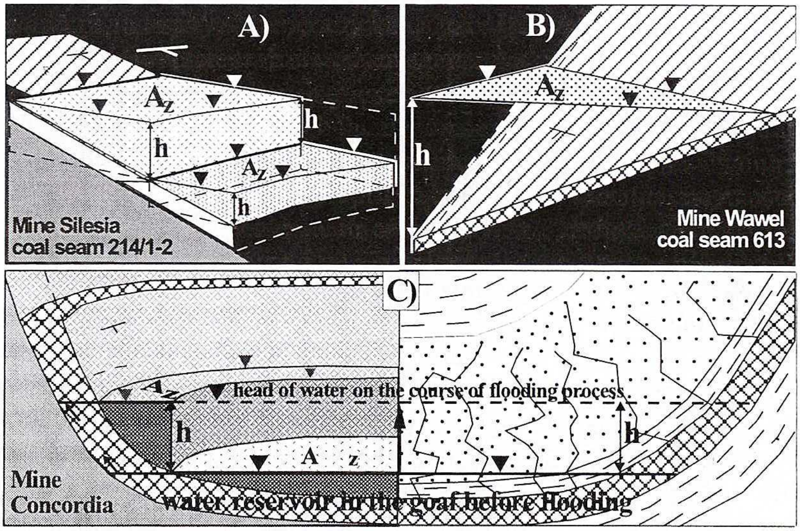

Fig. 4. Geometrical models used in calculations of the water capacity of rock masses and water capacity of post-mining fractures

A — half and full rectangular parallelepiped — mining perpendicular to strike and mining along strike; B — inverted pyramid — diagonal mining; C — the same as in A, with the axial part of the syncline taken into account

Rys. 4. Modele geometryczne zastosowane do obliczeń pojemności wodnej górotworu i pojemności szczelin poeksploatacyjnych

A — dla 1/2 prostopadłościanu i prostopadłościanu — eksploatacja poprzeczna lub podłużna; B — dla ostrosłupa odwróconego — eksploatacja diagonalna; C — jak w A, z uwzględnieniem wewnętrznej części synkliny

In the fold zone of the Concordia coal mine, in addition to the mine workings and strata of the syncline limbs, the strata of the syncline axis were also taken into account.

For both models, the calculations were made for the strata overlying and comprising the mine workings beneath the water table; the mine layout was determined and the goaf surface area was taken from a map. The void volume of the rock masses located beyond the outline of the mine workings, yet taking part in the reservoir formation, particularly, when the reservoir within the regional cone of depression is taken into account, could only be estimated roughly and with insufficient accuracy. The parameters of the total available void volume were mostly calculated for the old mine, aged several to a dozen or so years and only in the case of the reservoirs formed in the Morcinek and Marcel coal mines shortly after the interruption and termination of mining activity.

5.2. Characteristics of the partially of void volumes of water-reservoir in the light of in-situ studies

The proportion of each partially void volume of the total void volumes of the underground water reservoirs analysed, in respect of the related, differentiated influences of natural factors, was based on both theoretical calculations and field observations.

It has been found that in different geological conditions commonly encountered in different parts of the USCB and in different litho-stratigraphic series there are different void volume components among the reservoirs selected for examination. The individual types of partial void volumes in the total void volume of each water reservoir, which defines the reservoirs' void volume structure, are shown in Fig. 5.

Without taking into account the additional water capacity and discounting the water capacity of passageways, it is important to note that in seven of nine water reservoirs, the goaf constitutes the greatest partially void volume. It was found that the total void volume of the goaf was only exceeded to an insignificant extent by the total void volume of the post-mining rock fracturing in the Morcinek coal mine, and by the water capacity of the rock masses in the Silesia coal mine. In the latter case the rock mass was composed of nearly 85% sandstone. In general, in all the reservoirs surrounded by strata of low permeability, low gravity-drainage capacity and high strength, the second dominant total void volume following the total void volume of the goaf was the total void volume of the post-mining rock fracturing. The water capacity of the rock masses in such reservoirs can be much smaller, especially in the case of small reservoirs located at great depths. The shallow large-size reservoirs show a predominance of the total void volume of rock masses over the total void volume of the post-mining rock fracturing, the volume of which, in the case of near-surface reservoirs can be almost completely absent. Considering the partially void volume with respect to the additional capacity, we can easily discern that the latter forms an important partially void volume component of the total available void volume of such reservoirs. As far as the Marcel coal mine (tectonic engagement) and the Morcinek coal mine ("fresh" goaf following the coal extraction,

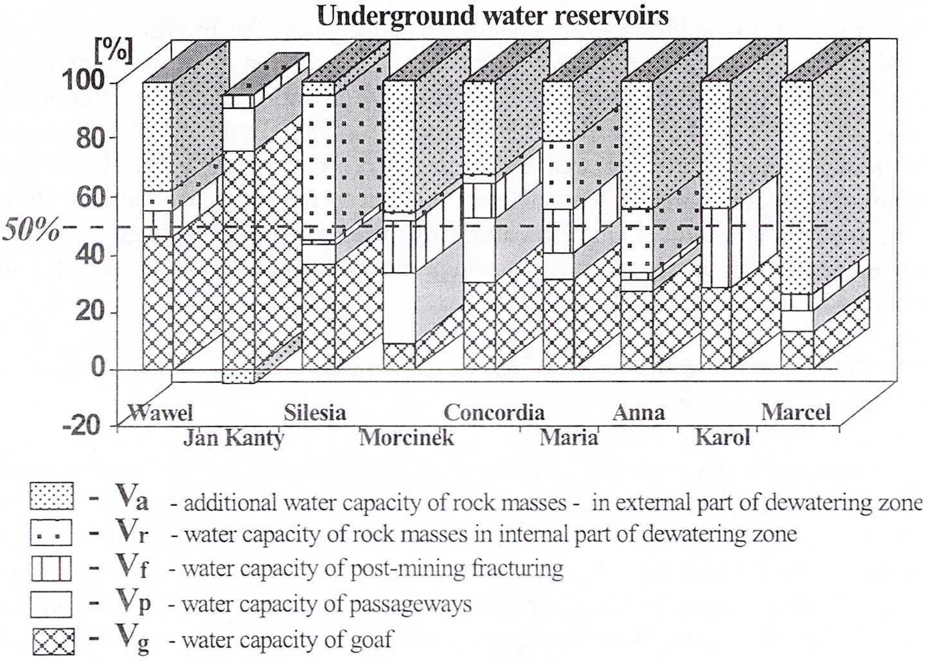

Fig. 5. Diagram comparing structures of the water reservoirs with respect to their partial void volume participation

Rys. 5. Diagram porównawczy struktur analizowanych zbiorników wodnych — udział poszczególnych składowych pojemnościowych

surrounded by strong sandstone) are taken into account, the additional void volume of the rock masses can be crucially influential on the mine flooding and mine drainage process (Fig. 5).

6. The impact of the water storage capacity of rock mass on the flooding process of mine workings and their natural environment

When discussing the impact of the water storage capacity of the rock mass on the mine flooding process and the natural environment, it should be emphasized that it had great influence on the way in which water reservoirs formed. That impact has not yet been either accurately defined or even roughly estimated. There are only a few special instances in which the water capacity of the rock masses (as inter-granular spaces) overlying the flooded mine workings as well as the total void volume of the post-mining rock fracture zone have been calculated. No estimations of the water storage capacity of the rock mass and the additional capacity have yet been made. In this connection, the estimations of the amount of water that can be stored in reservoirs formed in mine workings may be attended by considerable errors.

According to the author's experience over many years, the process of flooding of mine workings and the surrounding strata up to a predicted head of water provides evidence that it takes longer than predicted. As a generalisation, this phenomenon can be considered typical for the majority of USCB mines. A typical course of this process may be particularly pronounced in the case of large reservoirs occupying the whole or major sections of abandoned mines. The difference between the real and predicted flooding time implies that the actual total void volume of such a reservoir can be greater than that predicted. However, the reservoir formation process can vary, largely depending on the conditions in which the process develops.

6.1. Water storage capacity of rock masses surrounding the strain-prone weak strata

The water storage capacity of weak rock mass, related to the concrete hydro-geological, mining and geological conditions mostly prevalent in the eastern part of the USCB, is chiefly linked to the inter-granular void spaces of rocks adjacent to the mine workings located within the Libiąż, Łaziska and Orzesze Series. The value of the water capacity of rock masses in internal part of the drainage zone (V_r), and the additional capacity (V_a) linked to the water storage capacity of rock mass (V_{rm}), generally tends to be high and causes the mine flooding rate to be slower than predicted. However, in spite of high proportion of sandstones in the Coal Measures geology, a higher-than-expected mine flooding rate is observed in this part of the USCB on occasion. This phenomenon, though showing an apparently lower water storage capacity of the rock mass, can, in reality, be caused by the specific conditions in which the process develops. It can be linked not only to the claystone formations surrounding the extrected seam and the low-strength rocks adjacent to the mine workings, but can also be induced by high clay binder content of sandstones and by the water-assisted consolidation process of the collapsed rock material. The duration of the saturation process for rocks of high clay binder content can often be much longer than in the case of rocks of similar porosity but lower such content. It is important to note that in the case of strata composed of weak sandstones, the favoured water pathways, such as rock fractures and fissures, are much less developed and partially or wholly occluded, so that the water level rises much more slowly than in the goaf space (Fig. 6).

In rare cases, the water storage capacity of a rock mass, comprising the water capacity of the rock masses in the internal part of drainage zone and the additional water capacity, can be denoted by "–" (the Jan Kanty coal mine — Fig. 4). This results from the manner of defining (relation 3) the additional capacity. In such cases the value of the water capacities related to the water storage capacity of the rock mass is assumed to be $V_{rm} = 0$. The negative sign before the value of the water storage capacity of the rock mass indicates an atypical mine flooding process and a higher than predicted reservoir formation rate. In the prognosis this can be calculated on the basis of the mean value of the coefficient of water capacity of the goaf for a given depth. The estimate of the water storage capacity of the rock mass, taking into account the value of the additional water

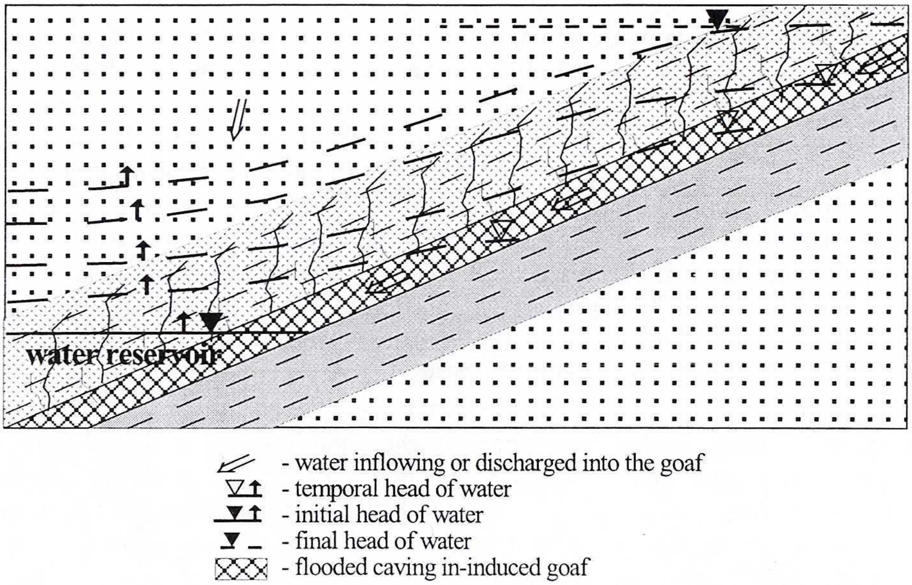

Fig. 6. Scheme of the flooding process of the goaf surrounded by claystones and weak sandstones of high clay binder content

Rys. 6. Schemat przebiegu procesu zatapiania zrobów w otoczeniu iłowców i słabych piaskowców o dużym udziale spoiwa ilastego

capacity (V_a assumes a negative value) should correct the total void volume of the reservoir formed. It can be important in assessment of the possible occurrence of a water-hazard — an indication of a possibly higher than predicted mine flooding rate.

In general, from the analysis of all available geological and mining data, including the results of laboratory examination of the Carboniferous rocks, two causes of shorter-than-predicted water reservoir formation times within a definite range of heads of water were found. The first cause of the reduced actual mine flooding time (for the Jan Kanty coal mine) indicated by the variation of the head of water in the goaf, can be attributed to the following factors:

- a minimal void volume of caved claystone material and also a minimal void volume of rock mass immediately overlying the goaf up to the temporary head of the water table,
- the existence of an early, very large water reservoir in the goaf, of the highest importance to the behaviour of void spaces, particularly to the total void volume of the goaf (consolidation process) and to the possible lowering of the coefficient of water capacity of the goaf "c", compared with that calculated for the average caved roof-rock debris at the same level,
- an accumulation of swelling-prone minerals within the claystone formations and their admixtures within the overlying sandstone bed as well as thin claystone intercalation in the sandstone deposit overlying the goaf,

- low strength and considerably deformability of near-yield point rocks where the deformation processes can additionally be amplified by the mining system and the presence of water in the goaf.

Shorter-than-predicted mine flooding occurred in two out of five calculation intervals assigned for the analysis of the water reservoir formation process in the goaf of the Silesia coal mine. During the initial phase of reservoir formation in the Silesia coal mine, the cause of the shortened flooding time was similar to that in the Jan Kanty mine. During the final phase of the reservoir formation, a similar mine-flooding process occurred, despite the presence of a large proportion of high open porosity (up to 20%) sandstone sediments and the highest range of water table variation in the goaf. And so, despite the availability of strata capable of holding high volumes in the re-flooding process, compared with the remaining calculation intervals, there were fewer than predicted void spaces capable of storing free water and less chance for infiltration of water into the rock pores. This, particularly, relates to difficulties for the water to move freely and to saturate strata lying farther away from the mine workings. Thus, in the mine workings accumulating discharged water, an inverted cone of depression resulted and even a high open porosity of the sandstone sediments adjacent to the mine workings was unable to bring about a substantial slowing of the mine flooding process. The void space flooding-rate at some water table levels can be higher than the rock-mass saturation rate (Fig. 6) and at the other intervals can be markedly lower.

From the above statement and the diversity of the rock mass structure, it has been found that the mine flooding time can vary distinctly on the scale of a mine or mine section. These variations, irrespective of technical reasons (for example, cessation of mining has an essential impact on the progression of the process when an estimation of how long protective measures will continue lacking), chiefly depend on the way the water inflow and the total void volume available for flooding are estimated. It is of the highest importance to the mines of the eastern and south-eastern parts of the USCB, where the mine flooding process can, above all, be linked to the high proportion of the rocks of high water storage capacity in the geological structure. Therefore, both the Carboniferous sandstone deposit gravity-drainage capacity determination procedure and the flooding-time estimate, assessments of rock mass quality and the geo-mechanical properties of rocks are the main data set for factors determining the prediction accuracy.

6.2. Water storage capacity of a rock mass with low-strain and strong competent rock masses

Let us consider the mine flooding process within strata composed of consolidated rocks, including the sandstones, mudstones and claystones of the Upper Silesian Mudstone or Sandstone Series, as well as the Paralic Series of the central, western and south-western parts of the Upper Silesian Coal Basin. The reservoirs surrounded by such rock formations, filling up with water and for which a detailed void-volume analysis was performed showed very low values of rock-mass water capacity in the internal part of the drainage zone. Values for the additional water capacity were very high. In general, this may be linked to the low open porosity of the rock and gravity drainage capacity of Carboniferous sandstone deposits. On the other hand it may be linked to a significant extension of the primarily drained natural and post-mining rock fractures and their higher-than-expected new potential to store water. It is important to note that the mine flooding process depends on the following local mining and geological conditions: depth, mining system, geo-technical parameters of rocks, tectonics and to some extent, the lithology and hydro-geological properties of rocks.

Water may flow relatively fast throughout the aquifer for great distances using fractures of high potential water capacity, notwithstanding the poor permeability of such rocks (delayed pore permeability — Fig. 7). This can be conducive to the water-rock interface growth to produce a substantial increase in the water storage capacity of the rock mass.

From the monitoring and prognostic calculations performed, it was found that the real formation process of a reservoir surrounded by competent rock masses will, despite its generally low water storage capacity, often last longer than expected from the lithological and computational indications. The value of the total void volume of the goaf calculated for USCB hard-coal mines can be many times lower than the value of the total available void volume of the water reservoir. Consequently, the predicted times for filling mine workings with water do not compare to the actual times. This chiefly results from the flooding of drained rock fractures, mostly natural and partly post-mining, and from their considerable extension in rock masses made up of competent rocks.

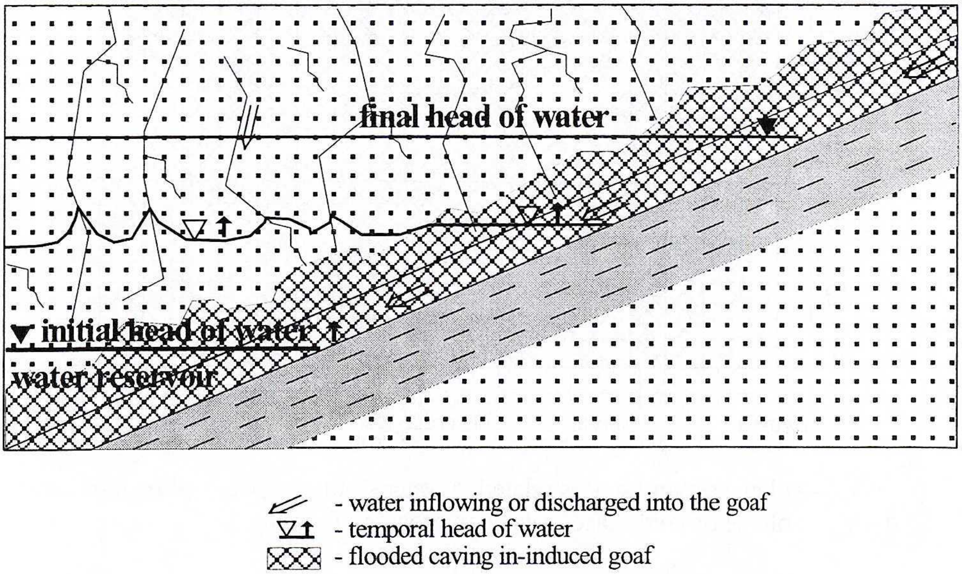

Fig. 7. Scheme of the flooding process of the goaf surrounded by strong and strain-resistant rocks

Rys. 7. Schemat przebiegu procesu zatapiania zrobów w otoczeniu skał „mocnych", mało podatnych na odkształcenia o charakterze zbliżonym do plastycznego

6.3. The importance of the water storage capacity of a rock mass to the flooding process of mine workings and their natural surroundings

Defining all the partially void volumes on the basis of prognostic calculations and subsequent site monitoring data allows a full image of the water reservoir structure formed and the impact of its partial void volumes on the flooding process to be obtained (Fig. 8).

Each partially void volume percentage of the empirically determined total available void volume of the reservoir can be proportionally responsible for its formation time and the way in which the process takes place. When the total available void volume of the reservoir is divided into the void volume related to the water storage capacity of rock mass (V_{rm}) and void volume related to mining activity (V_m), the proportion of these capacities in the underground water reservoir formation process will be from about 35% to 75% (on the average 50% — Fig. 8).

From the discussion on the impact of the water storage capacity of rock mass on the goaf flooding process, we can deduce that this parameter will be equally influential as as that of the total void volume related to mining (Fig. 8). It may, in fact, actually double the mine flooding time, compared with the time predicted using established methods.

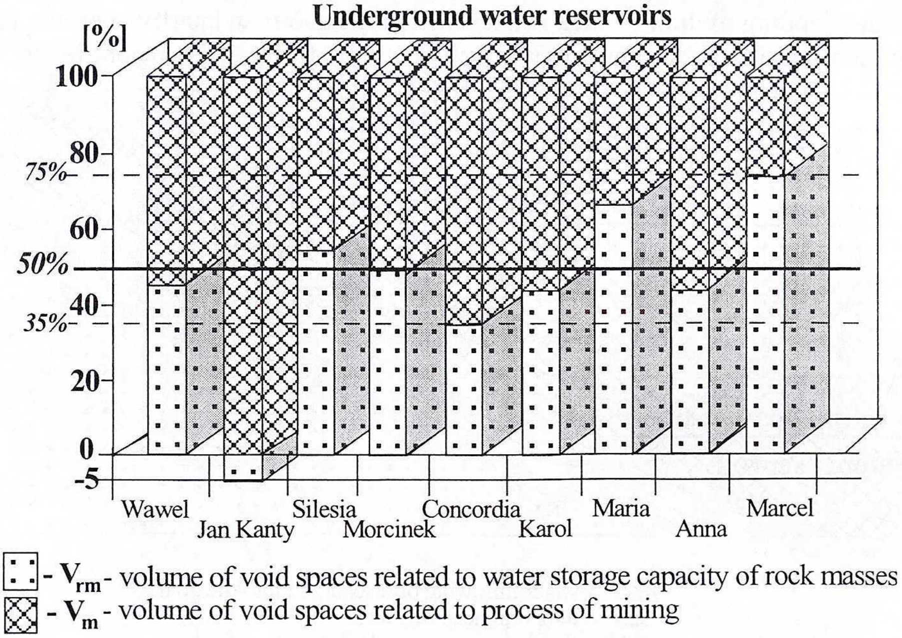

Fig. 8. Water storage capacity of rock mass and its percentage of the total capacity of water reservoirs under study

Rys. 8. Udział chłonności wodnej górotworu w ogólnej objętości wód w analizowanych zbiornikach

Moreover, mines significantly differing in geological conditions may show similar values for the water storage capacity of the rock mass. We can briefly state that the ratio of the water storage capacity of the rock mass to the total void volume of mine workings and post-mining rock fracturing for various parts of the USCB and for different conditions of water reservoirs does not undergo more significant changes (Fig. 8). However, within the partially void volumes of the water storage capacity of the rock mass, the ratio the volume of intergranular water to the volume of water in the rock fractures may vary (Fig. 5).

The water-storage capacity of the rock mass can directly influence the mine flooding time and on the progress of flooding in abandoned mine workings. It can also indirectly be of great importance for the assessment and prediction of the reservoir formation-related water hazards.

7. Determination and assessment of the water storage capacity of a rock mass parameters

The basic, calculable parameters needed for studies of the mine flooding process can, on the one hand, be those useful in the estimation of the mining-related partially void volumes such as those of goaf, passageways and post-mining rock fracturing as obtained and presented by Rogoż (1978). On the other hand, these are parameters that can be used in assessing the total void volume of rock masses available for flooding, by using geometrical models and the storage coefficients as measures of the gravity-drainage capacity of rocks — only free water determined. As a result, these parameters allow the water storage capacity of a rock mass to be calculated (Bukowski 1999, 1999a, 2000, 2001). Geometrical models were also used in assessing the portion of post-mining rock fracturing involved in the flooding process. The author wants, in particular, to take into account the way the parameters describing the water storage capacity of the rock mass, including its void volume, can be calculated. Therefore the author suggests using the storage coefficient in calculations that would only define the rock void space volumes available both for flooding and gravity draining and using simple geometrical methods in calculating the volume of rock mass involved in the process of flooding (Bukowski 1999a). This particularly applies to computer software program-related calculations.

When considering the analysis of the rock-mass water-storage capacity calculation results for the reservoirs monitored, for the information to be used more widely in mines, the author, besides the other parameters discussed earlier, suggests determining the so-called "**rock-mass water-storage capacity index**." This index, defined for the whole of a reservoir, can correct the total void volumes of underground water reservoirs in mine workings by introducing a value of the water storage capacity of the rock mass for their local cones of depression. This is the ratio of the real empirical void volume of the reservoir (V) to the total void volume of the goaf and passageways ($V_g + V_p$) denoted by "d_{rm}". When the total void volumes of the post-mining rock fissures and fracturing is taken into account the rock-mass water-storage capacity index is denoted by D_{rm}.

Considering the method of making calculations for underground water reservoirs in hard coal mines, which are generally only based on the total void volume of mine workings, only the above mentioned partially void volumes (goafs and passageways) can be included in the formulation:

$$d_{rm} = \frac{V}{V_g + V_p} \tag{9}$$

The values of index d_{rm} obtained for the reservoirs investigated are shown in Fig. 9. The values range from 0.95 to 4.78.

The lowest value of index $d_{rm} \cong 0.95$ (< 1.0) reflects a lack of water storage availability in the rock masses adjacent to the Jan Kanty hard coal mine reservoir consisting of claystone-type weak rocks. The highest values of the index are typical of water storage capacity of a Carboniferous rock mass in areas showing strong tectonic involvement such as the Marcel mine. The well developed tectonics of the area, in spite of the low permeability of rocks, significantly favour infiltration of water into the rock masses. The values of this index indicate the relationship between the water storage capacity of the rock mass-related waters and the waters of mine workings and post-mining rock fracturing overlying the excavations. A correction of the calculated total void volume of the USCB underground water reservoirs can be derived by multiplying the calculated total void volume of the reservoir by a carefully chosen index d_{rm} defined for similar mining and geological conditions.

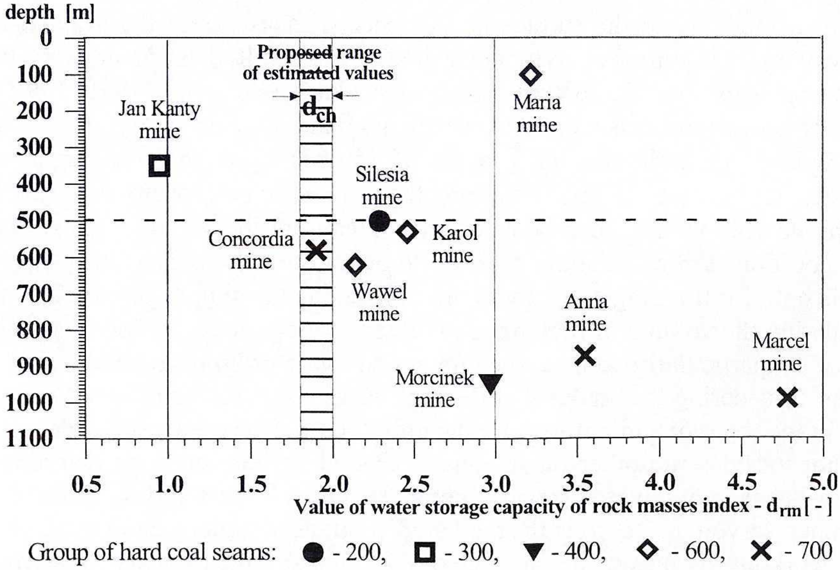

Fig. 9. Rock-mass water-storage capacity index d_{rm} versus depth and stratigraphic position of the flooded goaf

Rys. 9. Wskaźnik chłonności wodnej górotworu d_{rm} a głębokość i pozycja stratygraficzna zatopionych zrobów

Fig. 9 shows that the value of index d_{rm}, in spite of different geological conditions, can, with respect to almost all reservoirs, generally be in excess of 2.00. The value $d_{rm} \cong 1.80–2.00$, when calculated carefully for the reservoirs concerned, can be recommended to be of use in correcting the total available void volumes of the majority of USCB mine-water reservoirs. It can also be applied to the primary evaluation of reservoir formation and the drainage processes in active mines. Practical application of the index will only be possible if a similarity of location conditions of the reservoir can accurately be determined, i.e., if an accurate estimate of the water capacity of the goaf and passageways with respect to their clamp processes can be obtained.

The above mentioned parameters, allowing us to correct the total void volumes of the underground water reservoirs, should reduce the flooding process prediction error by approximately 50% and can also be widely used in predicting the mine working's draining process. The accurate evaluation of the water storage capacity of a rock mass with respect to the natural and mining conditions of mine workings and their surroundings may be of great importance in estimating the profitability of drainage associated with the existing reservoirs' water-hazard elimination program. It may also be of great importance for predicting possible hazards linked to the reservoir water recovery-induced methane emission. The methane, driven out by rising mine water, may accumulate in mining voids between the water table and the continuous layer of impervious rock formations. To calculate these void volumes mining induced the calculation methods as used in the studies described in this paper may be applied.

It is important to note that the relationship between the variability of the participation of the water storage capacity of the rock mass with parameter d_{rm}, and diversification of the mining and geological conditions in the Upper Silesian Coal Basin, requires further studies. These are currently being conducted by the author at the Central Mining Institute (GIG), Katowice.

Conclusions

From the Upper Silesian Coal Basin mines, flooding-monitoring results and the analysis of mining and geological data obtained from underground water reservoir sites (Bukowski 1999), a significant relationship between the water storage capacity of the rock mass and the dynamics of the mine flooding process has been found. Based on the results of the studies, the following conclusions have been drawn:

- In estimating the drained void space, the hydro-geological properties of the rock masses surrounding the mine workings and their moisture content should be taken into account. This estimate can be obtained using the storage coefficient as a measure of the gravity-drainage capacity (by the capillary saturation method — Bukowski 1999, 2001) or the rock's gravity drainage index; for the not objective sampling reason — more complicated and difficult method (Wilk and Szwabowicz 1965).

- The total void volume of the water reservoir formed in the goaf may, in general, vary from that predicted only when the total void volume of the mine workings, post-mining rock fracturing and water capacity of rocks in the internal part of the drainage zone (V_r) are taken into account. It may, generally, be greater than the figure calculated in the mine by the value of the empirically determined additional capacity of rock masses of the drainage zone (V_a). This difference can be shown by the real formation time of the reservoir being longer than predicted. A shorter actual formation time is found with reservoirs surrounded by weak claystone strata and clay binder sandstones. The water storage capacity of the rock-mass is the sum of the calculated values of capacities of rock masses in internal part of the drainage zone and the additional capacity expressed by the volume of water in the reservoir. It often brings about a "typical" progress in mine flooding, consisting of a significant prolongation of the flooding time as predicted by current methods.
- A more or less accurate image of the water reservoir structure formed of the impact of its partially void volumes on the course of the mine flooding process could only be given by all the partially void volumes determined on the basis of prognostic calculations and by subsequent site monitoring. A proportion of each partially void volume, calculated in relation to the empirically determined reservoir's real total capacity can proportionally be responsible for its formation time.
- The water storage capacity of the rock mass as a percentage share of the total void volume of each reservoir under study can be substantial in the majority of cases and may range from 35% to 75%. The mutual proportions of the amounts of water contained in the volume used in calculating the water storage capacity of the rock-mass with respect to the partial void volumes of the rocks' fissures and inter-granular spaces may undergo changes. For the reservoirs under study, it is important to note that the ratio of the proportion of rock-fracture water to the proportion of inter-granular water can, in general, grow with depth and reach high values. This was observed for example, in the case of the reservoirs formed in the areas of the Marcel, Anna and Morcinek coal mine, regarded as being connected with the tectonic development and containing goaf existent for only a short time.
- The rock-mass water-storage capacity index d_{rm}, determined in the study, is the parameter that allows the total void volume of water reservoirs calculated based on the methods frequently used by the mine's geological survey to be corrected. Its value depends on the local natural and mining conditions and for the 9 investigated reservoirs may range from 0,95 to 4,78.
- The results of the study of the water storage capacity of the rock mass and the related estimates may be widely used in predicting the flooding process in abandoned mine. It may also have applications in determining extent of the buffer zone as a proportion of the total void volume of reservoirs drained by deep pumping stations. The results of the study may be indirectly applied to the prediction of the volume of methane in mine workings and surrounding rock

masses and the methane gas-explosion hazard. They may be applied to the determination of volumes of free spaces designed to store water of high temperature or brine and to the estimation of water-hazard combating costs in connection with draining the underground water reservoirs in the active hard coal mines of the Upper Silesian Coal Basin area.

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