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Leak Tightness of Underground Carbon Dioxide Storage Sites and Safety of Underground CO₂ Storage by Example of the Upper Silesian Coal Basin (Poland)

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1. Introduction

The region of the Upper Silesian Coal Basin (USCB, southern Poland) was a subject of investigations referring to possibilities of underground storage of carbon dioxide. It is an industrial region characterized by high density of industrial infrastructure on the surface of the ground and underground as well as considerable emission of CO₂ into the atmosphere. Among significant objects one should mention the presence of 53 mines of hard coal (Fig. 1). In these mines, there is or was conducted in previous years exploitation of coal deposit to the depth of about 1000 m below the terrain surface level. Location of underground storage sites within a small distance from an industrial emitter of CO₂ might positively influence the cost-effectiveness of underground storage – if only by reducing costs of gas transport. However, with the current infrastructure, a selection of a proper site for storage necessitated conducting additional investigations, mainly detailed, multi-stage analysis of CO₂ injection safety. Below, there are presented outcomes obtained in the years 2007-2010 in the framework of the research project the Technological Initiative I, entitled: “*Study of safe carbon dioxide storage by example of the Silesian agglomeration*”, and dedicated researches carried out because of commissions received from concerned economic entities.

2. Selection of CO₂ storage location

Selection of suitable location of underground storage is a prerequisite for successful process of CCS (*carbon capture storage*). Prospective site for storage must be marked out by advantageous reservoir parameters, which was earlier mentioned by numerous researchers (Bachu et al., 2007; Bruining et al., 2004; Chadwick et al., 2008; Kumar et al., 2005; Obdam et al., 2003; Solik-Heliasz, 2010a). Both, safety of storage and effectiveness of CO₂ injection must be also ensured. In the course of conducted examinations it was found out that in the region of USCB, underground storage sites must be located only beyond areas of active and liquidated mines but also outside areas of urban agglomeration and huge industrial plants. It is so because it has been ascertained that areas of underground mining are potentially seismic regions. Rock mass parted with mine workings can be a source of vibrations, which in unfavourable hydrogeological conditions might activate new paths of underground water

migration as well as injected gas and lead to their unforeseen dislocation. Also areas of cities and large plants have been excluded from CO₂ storage – even at the deepest depths. In this case it does not, however, stem from some real threat but from a lack of sense of security which can concern the local community. In the investigated region it has also turned out to be crucial that prospective storage sites do not influence other undertakings of utilitarian character existing and planned in the vicinity of their borders. It can refer to both, workings of underground mines as well as water intakes, geothermal boreholes etc. Owing to the importance of the problem in question it became a subject of detailed investigations.

Having in mind the selected factors, the sandy and water-bearing horizon of the Dębowiec layers in the region of Skoczów-Zebrzydowice (Fig. 1) has been indicated for the injection of carbon dioxide. This horizon occurs in the forefield of USCB, beyond mines area, in overburden of coal series. Additionally, initially for the injection were qualified hard coal seams no. 405 and 510, deposited in the area of reserve mine field Pawłowice, at the depth of 1100-1500 m, as well as workings of hard coal mines Krupiński, Silesia and Brzeszcze – after their previous liquidation (Solik-Heliasz, 2010b).

The issue of safety of CO₂ injection was considered with reference to the area of the Skoczów-Zebrzydowice storage site. Nevertheless, the addressed problems can also refer to the remaining storage sites.

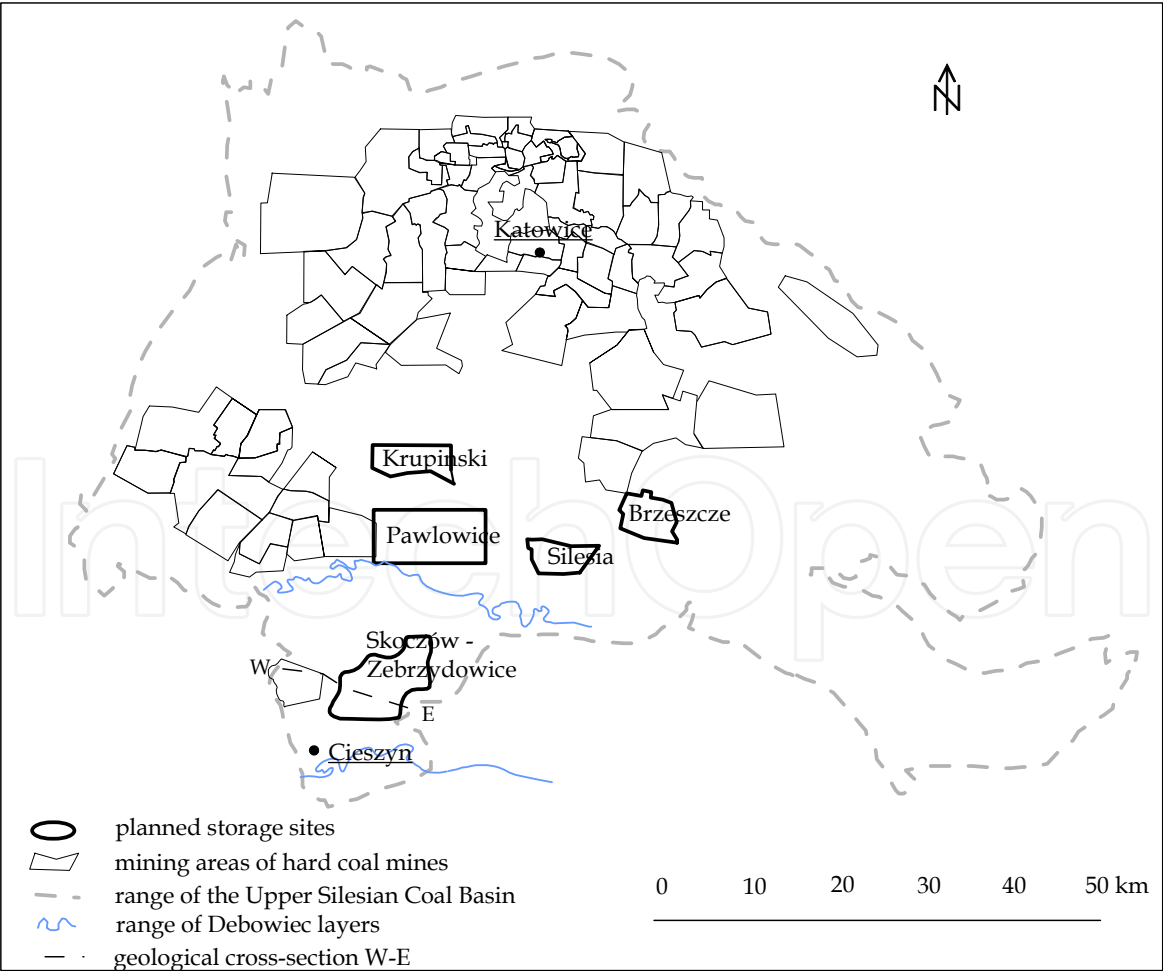


Fig. 1. Location of planned carbon dioxide storage sites in the region of USCB (Poland).

3. Examination of storage site leak tightness

Rock formations of the Skoczów-Zebrzydowice storage site are connected with Neogenic rock formations of the Dębowiec layers. They occur within the limits of regional structure of the Carpathian Foredeep, which stretches at the length of over 200 km along the southern border of Poland. The layers, deposited on morphologically diversified surface of carbon roof, are covered with thick complex of the Miocene claystones (Fig. 2). The existing hydrogeological conditions as well as parameters of reservoir rock formations, which are presented in Table 1, create favourable conditions for CO₂ storage. Nevertheless, the decisive role in the final selection of a site for injection played the analysis of storage site leak tightness and its potential influence on other underground objects in its vicinity. Leak tightness has been documented on the basis of geological cartography methods (maps, cross-sections), results of laboratory and *in situ* tests on hydro-geological and strength parameters of rocks, analyses of water chemical mechanism, results of geophysical tests and modelling.

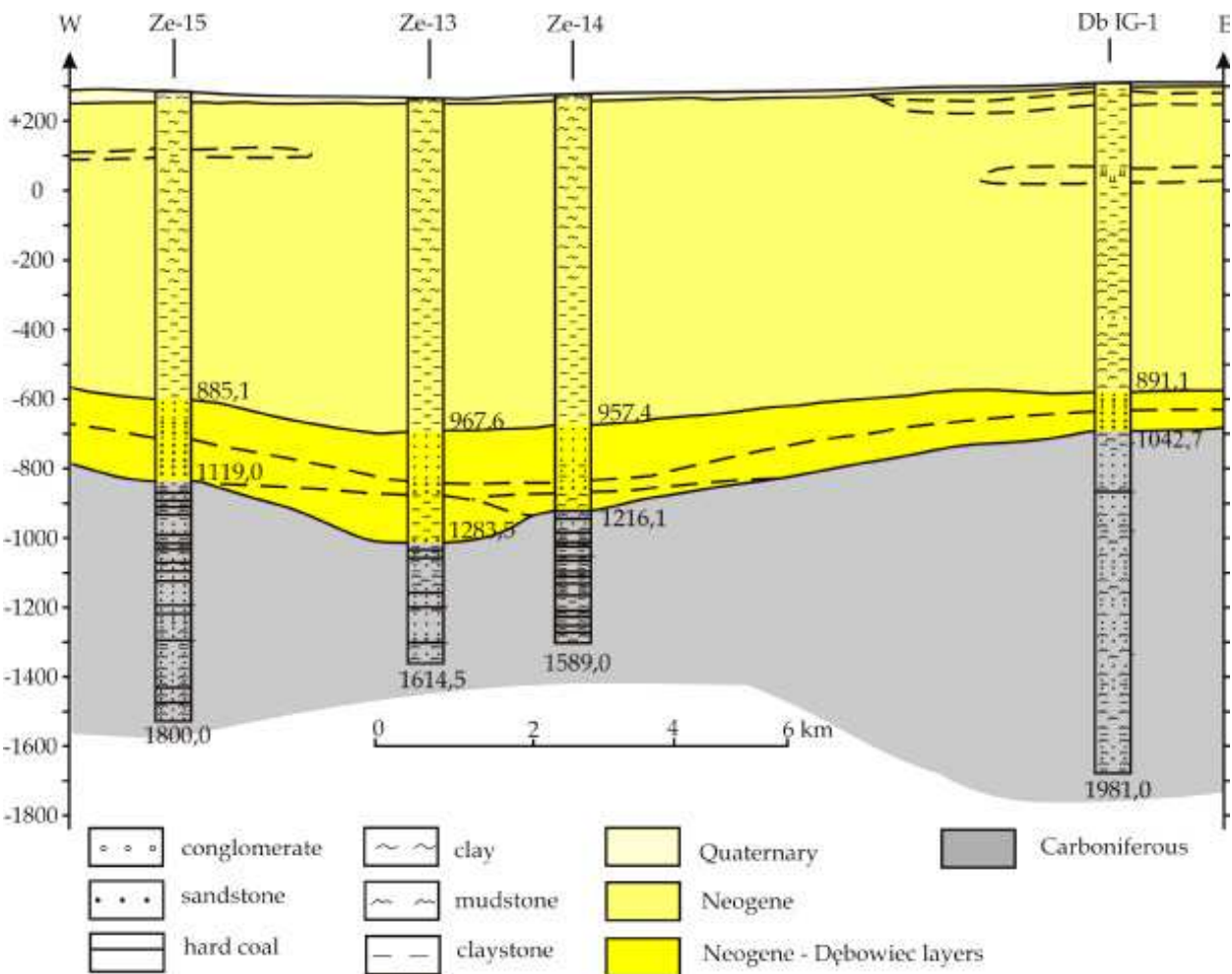


Fig. 2. Geological cross-section of the region of the Skoczów-Zebrzydowice storage site.

Rock parameters	Parameters values
Porosity of the Dębowiec layers rock formations [%]	8-15
Permeability of the Dębowiec layers rock formations [mD]	13-103
Compressive strength / tensile strength, R_c/R_t [MPa]:	
- rocks in overlay of the storage site	5.0-39.9/-
- storage site rock formations	4.0-56.0 / 0.1-2.4
- rocks in storage floor	26.9-44.7/1.8-3.8
Thickness of storage rock formations [m]	70-250
Thickness of isolation rock formations in storage roof [m]	720-1030
Effective CO ₂ storage capacity [Mg · 10 ⁶]	24.1

Table 1. Values of selected parameters of the Dębowiec layers in the area of the Skoczów-Zebrzydowice storage site.

The devised static model of the Dębowiec layers has shown that clay slates occurring in the overburden and in the floor of CO₂ reservoir are impenetrable. Leak tightness was also confirmed by chemical analyses of waters, their hydro-chemical indicators and isotopic composition of oxygen, $\delta^{18}O$. At the horizon of the Dębowiec layers, paleoinfiltrational waters have been found of Cl-Na and Cl-Na-Ca type, and mineralization up to 98 g/dm³. They indicate lack of connection between the hydraulic reservoir with the terrain surface.

Hindrance in a selection of storage site location turned out to be the neighbourhood of a large fault zone with 400-600 m displacement (Fig. 3). Results of hydro-geological investigations conducted in the workings of nearby hard coal mines have admittedly shown that this zone is not water filled. However, in case of carbon dioxide injection under pressure higher than primary hydrostatic pressure, its clearing cannot be excluded. As a result of this, the border of the storage site has been mapped out within a safe distance from the fault. A significant challenge turned out also a fact that water-bearing layer in the area of storage yard is not “closed” in its side part. Lack of “closing up” of storage site is a problem referring to many storage sites occurring in water-bearing horizons of regional character. In case of the storage site under examination, however, the knowledge of the height difference of the floor of the Dębowiec layers was applied. The storage site has been located in the area of two floor structural dips of layers forming local valleys about 300 m deep. In this way, the area of storage site was in considerable part contoured by natural geological frontiers, which should influence safety of CO₂ injection.

On the leak tightness of storage site will also have influence adopted parameters of carbon dioxide injection. A threat can particularly result from the adopted pressure of CO₂ injection. Too high pressure might lead to fracturing of reservoir rocks and/or neighbouring rocks. It is even more dangerous as rock formations of the Dębowiec layers display not too high values of strength parameters (Table 1). Fracturing of reservoir rocks is generally treated as a factor posing threat for storage safety. However – an opinion may be expressed here – that for reservoir rocks of medium and average values of hydro-geological parameters, controlled fracturing, limiting injection boreholes to the region can improve absorbing power of reservoir rock formations. In dynamic models of CO₂ propagation in the horizon of the Dębowiec layers, developed with the use of numerical programme TOUGH-2 (Pruess, 1991), effects of injection were analysed: 100 000, 300 000 and 500 000 Mg CO₂/year during the period of 30 years. As a result of CO₂ injection a repression cone will arise. It has

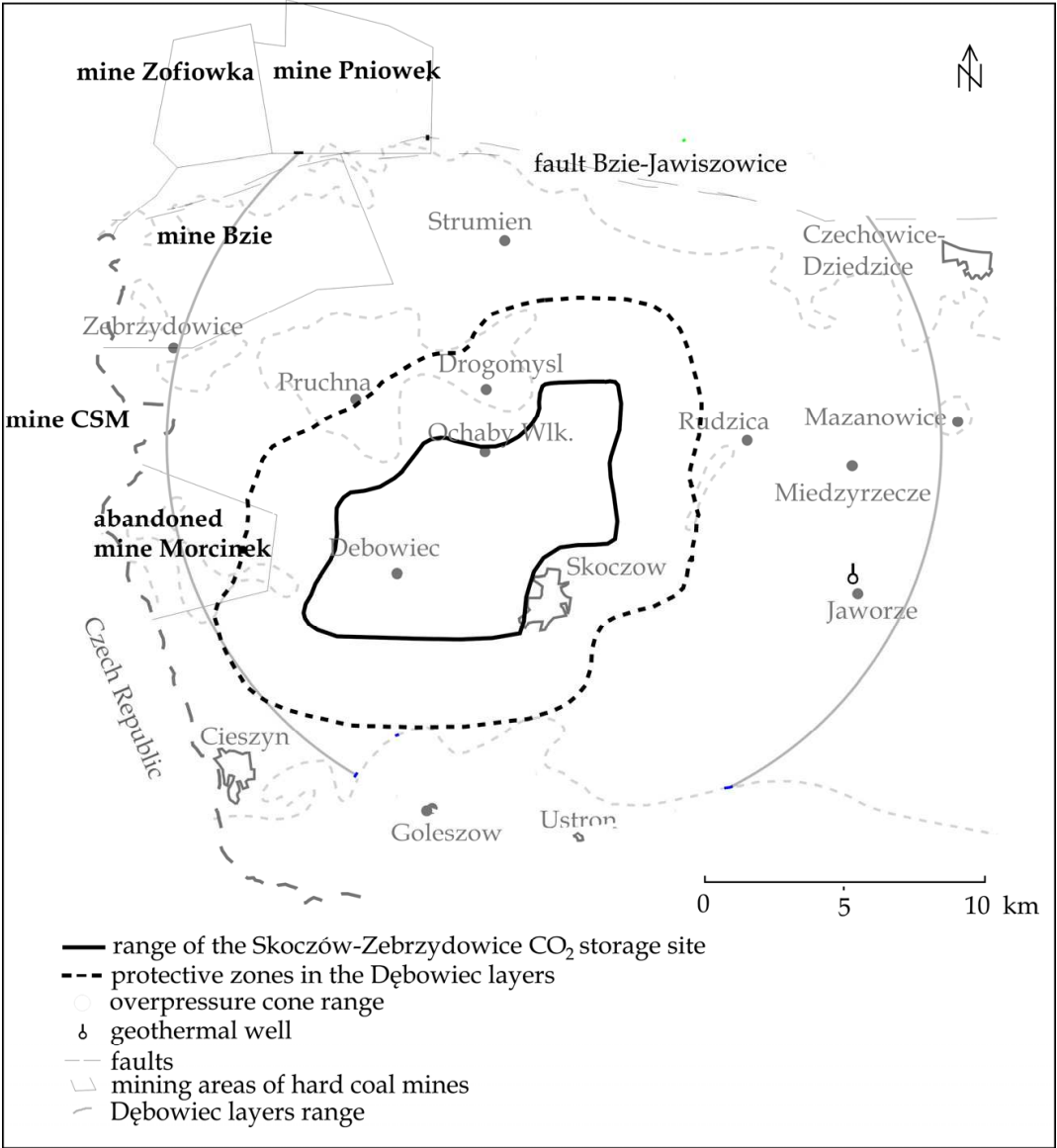
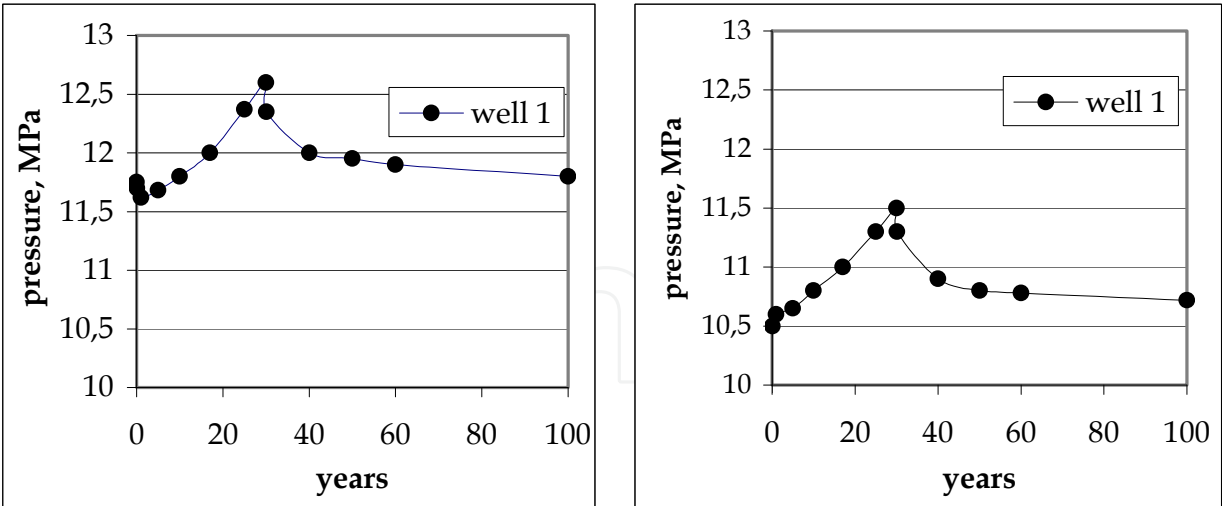


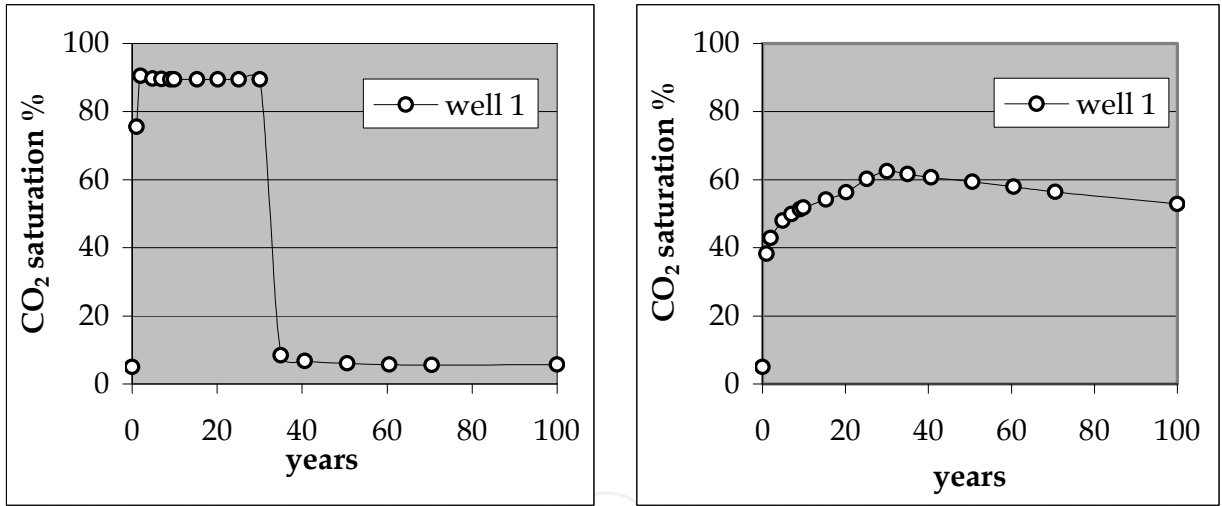
Fig. 3. Location of the Skoczów-Zebrzydowice storage site and major environmental features.

been ascertained that the optimum amount which can be injected through two injection boreholes amounts to $2 \times 150\,000 = 300\,000$ Mg/year. Injection of CO₂ into the floor part of the Dębowiec layers (Fig. 4a) will cause rapid increase of the pressure of water-gas medium in both holes from the initial value of 10.75 MPa to 12.6 MPa. During a short period of time maximum pressure in the region of injection boreholes can be similar to the pressure of rock fracturing. However, in the roof part of the Dębowiec layers the increase of pressure will mark itself much less clearly (Fig. 4b). On the other hand, saturation of water-bearing horizon with carbon dioxide will demonstrate unlike dynamics. During carbon dioxide injection (period of 0-30 years) CO₂ will be mainly accumulated in floor part of the Dębowiec layers (Fig. 5a). In the later period (period of 30-100 years), it will fill the space of the roof part (Fig. 5b). Results of analytical calculations confirmed that after 5 years of CO₂ injection, the radius of formed repression cone will amount to 11.8 km and encompass in its range both, storage site area as well as an area adjacent to it (Fig. 3).



(a) in floor part (b) in roof part

Fig. 4a,b. Pressure changes of water in the Dębowiec layers as a result of CO₂ injection in the amount of 300 000 Mg/year (according to Solik-Heliasz, on the basis of data obtained from Chećko, 2010).



(a) in floor part (b) in roof part

Fig. 5a,b. Distribution of CO₂ saturation in the Dębowiec layers (according to Solik-Heliasz, on the basis of data obtained from Chećko, 2010).

4. Analysis of storage site impact

Hitherto in Europe and in the world, locations of carbon dioxide storage sites are planned mainly in water-bearing horizons not utilized economically. This can however be subject to change due to building new underground objects. Then, a problem may arise connected with their interaction and a necessity to determine a safe distance between them. This problem has especially occurred in the examined region of USCB, especially with reference to workings of hard coal mines. From the conducted research works it follows that the approval of storage sites locations in industrialized regions or regions adjacent to them,

requires carrying out a detailed analysis of possible interactions. A two-stage analysis was performed. In the initial stage it covered determination of possible impact of storage site on other present and planned underground objects in its vicinity. In the subsequent stage an extreme scenario, in which consequences of possible penetration of CO₂ in the direction of other underground objects were analysed.

With reference to the Skoczów-Zebrzydowice storage site, it was examined how the storage site influences the following (Fig. 3):

1. planned geothermal water intake in the Dębowiec layers;
2. water-bearing horizon of the Dębowiec layers in the overburden of mines Morcinek and Bzie.

These objects are situated beyond the storage site area, thus a source of threat can come mainly from overpressure created in the horizon of the Dębowiec layers. In connection with this, it turned out justifiable to provide the answer to possible physical effects of overpressure. The results of preliminary analyses of simulations have shown that it can be (apart from rock formations fracturing mentioned before) the increase of water flow velocity in the horizon of the Dębowiec layers. With reference to the planned geothermal waters intake – the speed increase can cause increased water inflow to the intake and at the same time improve its effectiveness. On the other hand, with reference to the planned mine Bzie – in case of drainage of the Dębowiec layers in its area, which is to serve the increase of security of conducting mining exploitation – the increase of water flow might lead to increase of intakes to future drainage wellbores and as a result influence sooner attainment of the assumed depression of water level. The drainage process must be accurately monitored. It has been estimated that because of security reasons, arising cone of depression must not cross a border of protection zones established around the storage site (it will be developed in the further part of the work). In the extreme scenario, in contrast, the following were analysed:

1. results of possible penetration of CO₂ from the storage site to lower deposited workings in liquidated mine Morcinek;
2. threat to the stability of protecting pillar existing between workings of Polish mine Morcinek as well as active Czech mine ČSM.

Poor water leading of rock formations in the floor of storage site confirmed the results of *in situ* observations carried out during the functioning of mine Morcinek. Moreover, the dynamic model of the storage site area has not confirmed a possibility of carbon dioxide penetration into the foundation as well as its horizontal migration in the direction of mine workings. Despite that, the obtained results were treated with due caution. The numerical model requires designing a scheme of boundary conditions, whereas rock formations of storage site foundation constitute numerous interbedding of clay slates, mudstones and subordinately sandstones with coal seams. In spite of appropriate recognition of their parameters – general assessment of conductivity of this part is surely not sufficient. Thus, it turned out necessary to utilize the results of mining recognition as well as calculation methods applied in this field.

Workings of coal mine Morcinek are deposited at the depth of 750-1100 m below the terrain surface level. They are submerged and form huge reservoirs of underground waters. Their water capacity has been determined on the basis of calculation method by Rogoż (Rogoż,

2007) to be in total $2,3 \cdot 10^6 \text{ m}^3$ (Solik-Heliasz, ed., 2009). What is more, in side walls of a long network of mine workings: longwall, heading and drifts, occur remainders of hard coal deposits which can even amount to several dozen million tonnes. Results of laboratory analyses have shown that hard coal has substantial sorption capacity of carbon dioxide (Ceglarska-Stefańska et al., 2008). Table 2 presents CO₂ storage capacity in workings of selected mines, Krupiński and Silesia, in case of creating low-pressure reservoirs in them, of pressure $p < 0.6 \text{ MPa}$. These mines are situated in comparable geological conditions to mine Morcinek.

Parameters	Silesia Mine	Krupiński Mine
Volume of mine workings: longwall, passageway and caving fractures [$\text{m}^3 \cdot 10^6$]	25.08	5.80
Mass of left hard coal [$\text{Mg} \cdot 10^6$]	78.75	43.56
Total amount of CO ₂ possible to be stored in mine workings and in coal reminders [$\text{Mg} \cdot 10^6$]	2.9-6.7	0.9-1.9

Table 2. CO₂ storage capacity in workings and coal reminders in mines Silesia and Krupiński in GZW (Solik-Heliasz, 2010b).

The presented results show that workings of mine Morcinek are capable to absorb substantial amount of CO₂ in case of its potential migration from the Skoczów-Zebrzydowice storage site. Separate issue is a threat which can create the increase of water-gas medium in mine workings of mine Morcinek, on the stability of protecting pillar separating workings of this mine from workings of active mine ČSM (Fig. 3). The stability of the pillar has been verified on the basis of calculation methods utilized in underground mining. It turned out helpful to adopt i.a. the *Slesariew's* formula (Frolik, 1998), enabling to determine a safe pillar width:

$$D_{\min} = g \sqrt{60p}$$

(1)

where: D_{\min} – minimum width of protecting pillar, m

g - average thickness of reservoir series, m

p - target pressure in the reservoir, MPa.

Increase of pressure in abandoned working of mine Morcinek even by 50% in comparison to the primary hydrostatic pressure amounting to 7.8 MPa, will not threaten the stability of the existing pillar. Its present width which is 100 m will be sufficient.

Conducted examinations have shown that the process of the storage site exploitation does not encounter difficulties which could lead to its premature closure.

5. Will carbon dioxide storage sites require protection?

In EU Directive concerning underground storage of carbon dioxide (Directive, 2009) it is recommended that underground storage ought to be safe and injected carbon dioxide permanently bound with reservoir rock formations in the period of several hundred years and more. On the basis of its guidelines as well as experiences gained so far (i.a. Chadwick

et.al., 2008, Frolik et al., 2006), the ranges of storage sites in the area of USCB were established. Does it however mean that in the direct vicinity of storage sites – which theoretically should be safe - other utilitarian enterprises, e.g. water intakes, storage yards etc. can be located with complete confidence?

The rock formations of the Dębowiec layers mentioned above are characterised by changeability of hydro-geological parameters. Similar Carboniferous rock formations deposited in their floor, which additionally demonstrate high lithological diversification. Rocks of these two geological series are a subject of research conducted since the end of the 60's of the 20th century. Despite that, the diversification, which has been mentioned, can become a potential source of threat for safe storage of CO₂. Having that in consideration, it has been proposed to establish protection zones around CO₂ storage sites in USCB. They would constitute additional protection of storage sites against the influence of other utilitarian enterprises as well as other underground objects against storage site impact. Cap rock is a typical example of protection zones. Nonetheless, zones of this type should be also established in the side regions of the storage site and in its floor. The concept of protection zones location in various types of CO₂ storage sites are presented in Figures 6a-c.

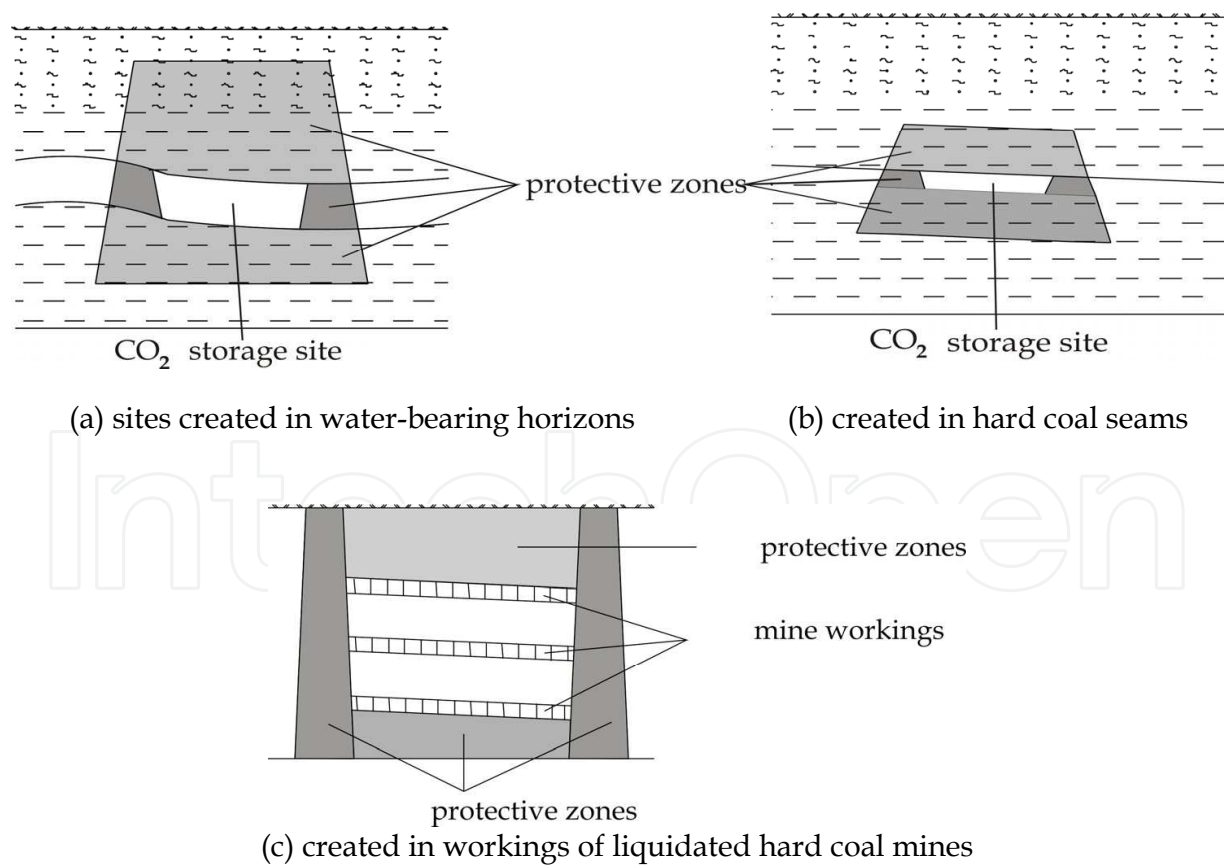


Fig. 6a-c. Concept of location of protection zones for carbon dioxide storage sites.

Methodology of delineation of protection zones width ought to become a subject of further research. Preliminary calculations made on the basis of the formula (1), with the assumption that CO₂ carrier after its injection into reservoir rock formations will be the flow of underground waters, have shown that the width of protection zones can be diversified. Appropriate values are presented in Table 3.

Location of protection zones for CO ₂ storage sites situated in:	Minimum width of protection zones in reservoir rock formations	Notice
	m	
Water-bearing horizon - in the region of CO ₂ storage site Skoczów-Zebrzydowice	2540-2920	High-pressure CO ₂ reservoir; $p \geq 10.75 \text{ MPa}$
Hard coal seams 405 and 510 - in the area of CO ₂ storage site Pawłowice	147-196	High-pressure CO ₂ reservoir; $p = 10 \text{ MPa}$
Workings of hard coal mines Krupiński and Silesia – after their liquidation	1800-2400	Low-pressure CO ₂ reservoirs; $p < 0.6 \text{ MPa}$

Table 3. Minimum width of protection zones around underground carbon dioxide storage sites in the area of USCB (Poland).

Delineation of protection zones around carbon dioxide storage sites can have, however, economical aspect, as it requires exclusion of additional parts of rock mass from economic activity. Nevertheless, the growing number of utilitarian enterprises in water filled rock series causes that they may require introduction of additional protection measures for them.

6. Conclusions

There is a possibility to create carbon dioxide storage site in the region adjacent to highly industrialised area of USCB. However, approval of its location took place only after conducting tests on storage site leak tightness and two-stage analyses of its potential impact on other underground objects located in the vicinity (workings of hard coal mines, water intakes). For the assessment of carbon dioxide storage safety, results of model research have been used which were supplemented with results of mining recognition (hydrodynamic regime in the area of the surrounding mine workings of the abandoned hard coal mine) using the calculation methods utilized in this field (connected with water capacity of mine workings, minimum width of the protecting pillars and their stability). The Skoczów-Zebrzydowice storage site will not negatively influence other underground objects in its vicinity. However, due to the fact that their number can increase in the future, it has been proposed to establish protection zone around storage site. It will constitute additional protection and determine intransgressible influence boundary of other underground objects planned to be built nearby.

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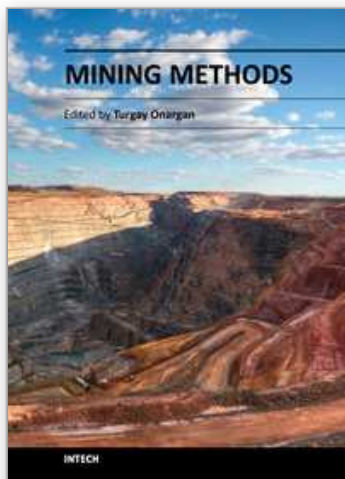
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An economic viability of a modern day mine is highly dependent upon careful planning and management. Declining trends in average ore grades, increasing mining costs and environmental considerations will ensure that this situation will remain in the foreseeable future. This book describes mining methods for the surface and underground mineral deposits. The methods are generalized and focus on typical applications from different mining areas around the world, keeping in mind, however, that every mineral deposit, with its geology, grade, shape, and volume, is unique. The book will serve as a useful resource for researchers, engineers and managers working in the mining industry, as well as for universities, non-governmental organizations, legal organizations, financial institutions and students and lecturers in mining engineering.

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