Monitoring the shallow subsurface for gas emission from abandoned underground mines

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Abstract In this paper, a risk-based method is proposed for the design of networks of piezometers for the monitoring of near-surface gas emissions from abandoned underground coal mines. Risk is evaluated considering the location and extent of the mine and of the former underground mining infrastructures. Damage induced by the mining works on the upper geological formations and the associated increase in permeability is also taken into consideration, as well as potential impacts on humans. Damage is estimated using an empirical method based on the number of caved seams between the ground surface and a depth of 200 m.

Keywords surface gas emanation, GIS, risk assessment, damage function

Introduction

Underground storage of gas in natural or man-made cavities must be accompanied by appropriate monitoring measures to ensure that the gas is not leaking from the storage site, migrating upwards through the soil and reaching the soil surface. Properly designed monitoring networks include three types of monitoring points: (i) near all remaining surface mining installations, (ii) near potential accumulation zones in the underground sewer system or in housing basements, and (iii) near areas of the former mine where gas is likely to accumulate and migrate upward towards the ground surface. The appearance of near-surface gas emanations can be monitored using piezometers installed in geological layers overlying potential accumulation zones in the mined voids.

In this paper, we propose a method to design a network of piezometers aimed at monitoring potential gas emanations in shallow geological units. The method is based on an assessment of the risk to human population and is implemented within a GIS (Geographic Information System). It considers the location and extent of the mined areas, the ease of gas migration towards the ground surface, and the distance to the nearest housings.

The methodology is applied to two former gas storage sites installed in the abandoned coal mines of Péronnes-lez-Binche and Anderlues, in Belgium. When decommissioning the gas storage sites, it was recommended that the existing monitoring networks for surface gas emanations were complemented with additional piezometers. In this study, a preliminary assessment of the risk linked to surface gas emanations from the former storage sites is conducted and several suitable locations are identified for the installation of new piezometers.

Geographic and geological setting

The area of interest is located north and east of the city of Binche (Fig. 1) and takes to form of two imbricated areas framing the concessions of the coal mines in which natural gas was stored. The former gas storage site of Péronnes-lez-Binche fits within a rectangle of about 8 × 4 km², while that of Anderlues fits within a rectangle of about 4 × 4 km².

The average elevation of the zone is about +130 m a.s.l. In the western part of the zone (former storage site of Péronnes-lez-Binche), landscape is essentially marked by the valley of a small creek, flowing from South to North.

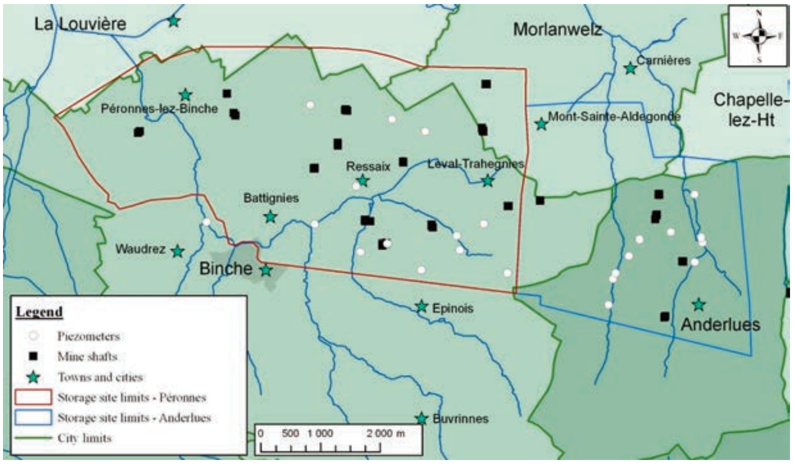

Fig. 1 *Geographic extent of the former storage sites.*

Surface elevations progressively increase from about +50 m a.s.l. in the northwest to about +180 m a.s.l. in the southwest of the zone.

In the eastern part of the zone (Anderlues), landscape is marked by two valleys with small creeks also running from South to North. Surface elevations range from about +110 m a.s.l. at the bottom of the valleys to about +220 m a.s.l. in the southern part of the zone.

Population density is highly variable. The city of Binche is an important urban nucleus (Fig. 1). A couple of smaller towns (Péronnes-lez-Binche, Battignies, Ressaix, and Leval-Trahegnies) also constitute more densely populated areas. Elsewhere, lands are mainly used for agriculture.

The stratigraphic sequence is characterized by a Carboniferous basement covered with Cretaceous and Tertiary sediments. Cretaceous units consist of marls of Turonian age and chalks. Turonian marls constitute a relatively continuous and impervious cover over the mined bedrock. Their average thickness is in the range of 20–30 m. They act as a hydraulic barrier and confine the gas that was stored in the former mines. The average thickness of the chalks is 60 m but can locally reach up to 100 m. The aquifer of the chalks is the main regional aquifer. It is an unconfined aquifer that is relatively heavily tapped for drinking-water production. Finally, tertiary sediments are mainly sands and clays. Kaufmann and Martin (2008) developed a full 3D geological model of the area that was used in this study.

Risk assessment

Risk assessment is conducted considering the simultaneous occurrence of (i) a source of danger, (ii) a pathway from the source to targets, and (iii) the presence of targets within distance of the source. Table 1 lists the variables that are used to quantify the components of risk. First, the source of danger is linked to the presence of exploited coal seams at a depth of less than

Component	Relevant element	Influence on the global level of risk
Source	Mined voids at a depth of less than about 200 m.	Risk is considered as negligible if no mined area can be found above a depth of about 200 m
Pathway	Minimum depth to mined voids	Risk increases where mined voids are closer to ground surface
	Geology / hydrogeology	Risk decreases in zones where low-permeability geological units are thicker (i.e. marl, clay, …)
	Damage to geological layers resulting from mining activities	Risk increases if damage to upper geological layers is important. Damage is directly linked to the distribution of mined voids.
Target	Distance to nearest habitations	Risk decreases in zones where the distance from the point of surface emanation to the nearest targets increases.

Table 1 *Relevant variables for risk assessment.*

about 200 m. While this value is relatively arbitrary, it is usually considered that significant ground damage will not occur at more than 150–170 m above a caved coal seam. It is considered that gas accumulating at larger depths is not likely to migrate towards the ground surface. Then, the pathway component is primarily evaluated based on the geology and on the damage linked to coal exploitation. Only vertical pathways are considered here: gas is assumed to migrate vertically. Finally, as the risk associated to surface gas emanations is primarily gas accumulation within a confined space and explosion, it is considered that any human being within distance of a zone where gas emanation could occur is at risk. The target component is quantified as the distance to the nearest housings. As the distance increases, the likelihood that gas accumulated in or near the housings decreases.

Source component

Regional-scale cross-sections of the mine were used to identify near-surface coal seams. Such cross-sections are three-kilometre-long North-South-oriented vertical cross-sections, generally available every 100 m along the West-East direction. They cover the whole territory and contain information from all existing mine concessions. Exploited coal seams are represented on the cross-sections, as well as the main access shafts and the connection tunnels. The ground surface and the limit between coal bearing units and upper non-Carboniferous units is also represented, with a limited precision considering that there is no vertical exaggeration.

A total of 267 cross-sections have been examined. If multiple copies of one cross-section were available, the most penalizing with respect to gas migration towards the surface was always kept. A 100 m × 100 m horizontal grid was adopted to analyze the cross-sections. The number of exploited coal seams between the ground surface and a depth of about 200 m was counted for each grid cell, as well as the depth to the shallowest exploitations, if there were any between the ground surface and a depth of about 200 m. Considering the vertical scale of the cross-sections and that the analysis was conducted manually and visually, depth measurement precision is estimated at about 10 m.

As an example, Fig. 2 shows the spatial distribution of the number of exploited coal seams. Most of the time, between 1 and 3 coal seams are identified per grid cell. There is however a relatively significant portion of the Péronnes-lez-Binche reservoir where the number of exploited coal seams increases up to 6. It only increases up to 9 in one area, and up to 12 in another area. In Anderlues, exploitations were generally much deeper than 200 m. Mined coal seams outside of the Péronnes-lez-Binche and Anderlues concession correspond to neighboring concessions.

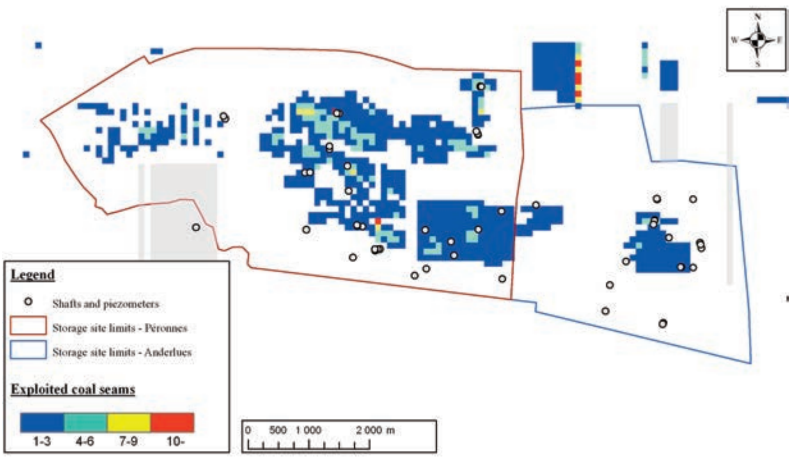

***Fig. 2** Number of exploited coal seams between the ground surface and a depth of about 200 m. Gray areas correspond to zones where no cross-section was available.*

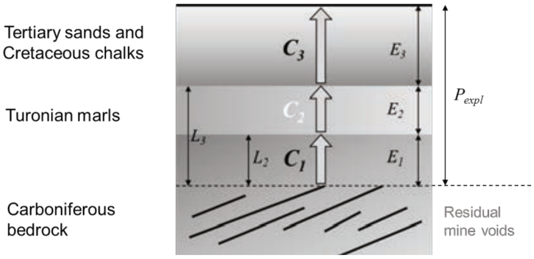

Fig. 3 *Definition of the variables needed to compute specific hydraulic conductance.*

Pathway component

The conceptual model used to quantify the pathway component uses the notion of specific hydraulic conductance (Harbaugh *et al.* 2000). Specific conductance is defined as the ratio of the permeability to the thickness of the geological layer. Based on Darcy's law for fluid flow in porous media, multiplying specific conductance by head difference and cross-sectional area for flow gives the total discharge. Hence, if permeability increases, gas will migrate towards the ground surface more easily. Similarly, for a given pressure difference, if thickness decreases, gradient and flow rate will increase.

The general model used for the storage sites of Péronnes-lez-Binche and Anderlues is depicted on Fig. 3. Three types of geological units are considered: the Carboniferous bedrock, the Turonian marls, and the upper chalk units and tertiary sands. Total specific conductance C_{tot} is computed using a serial model of the specific conductance of the Carboniferous bedrock (C_1), of the Turonian marls (C_2) and of the Tertiary sands and the Cretaceous chalks (C_3)

$$\frac{1}{C_{tot}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} = \frac{E_1}{K_1} + \frac{E_2}{K_2} + \frac{E_3}{K_3} \quad (1)$$

Subscript indices 1, 2 and 3 will refer to the Carboniferous bedrock, to the Turonian marls, and to the Tertiary/Cretaceous cover, respectively. The thicknesses of the geological units (E_1, E_2, E_3) are directly obtained from the geological model of Kaufmann and Martin (2008).

Permeabilities (K_1, K_2, K_3) depend on the geology and on the presence of nearby exploited coal seams. Indeed, mining activities can cause important ground fissuring and stress release in the bedrock and the upper geological units, sometimes resulting in important perturbations of subsurface permeabilities. In this paper, it is proposed to link the permeability of the damaged geological unit to its initial permeability using a mathematical model accounting for the damage caused by the underground exploitations.

The evaluation of the area impacted by the mining activities and the level of damage is relatively complex and depends on the nature and the geometry of mining works, on the nature and mechanical properties of the overlying rocks, on the method of roof control (caving or back-filling), on the local and regional tectonic contexts and on the local stress state of the rock. In this paper, it is proposed to adopt an empirical approach based on a damage function for the evaluation of the effect of underground mining activities on permeabilities. The damage function allows the determination of a dimensionless coefficient D [-], based on the density of mining works (*i.e.* number of coal seams exploited between 0 and -200 m, noted N_V [-]), and the distance L [m] to the mining works. The damage coefficient ranges from 0 to 1. The choice of the damage function is relatively arbitrary, provided that

- the function exhibits a maximum for a minimum distance and a maximum number of exploited coal seams;
- the function tends towards zero if the distance to the nearest exploitations increases, independently of the number of exploited coal seams;
- the function equals zero if the number of exploited coal seams is zero;
- the function increases with the number of exploited coal seams, for a given distance to the nearest exploitations.

The function proposed here is characterized by 4 parameters:

- a minimum distance L_{min}, under which damage is also maximum for a given number of exploited coal seams;
- a maximum distance L_{max}, beyond which damage is negligible;
- a maximum number of exploitation coal seams $N_{v,max}$, corresponding to a unit damage index D at short distance;
- a dimensionless shape factor F >1 controlling the shape of the damage function.

The proposed damage function is best expressed using complex variables. One defines

$$x = \frac{N_v}{F \times N_{v,max}},\quad y = \frac{10(L - L_{min})}{(L_{max} - L_{min})},\quad z = x + iy \qquad (2a, b, c)$$

where i is the complex number, with $i^2 = -1$. The damage index is given by

$$D = \log\left(\frac{1+z}{1-z}\right) \Big/ \log\left(\frac{1+F}{1-F}\right) \qquad (3)$$

Two example applications of the damage function corresponding to two different values of the shape parameter F are shown in Fig. 4. In the remaining part of the text, the values L_{min} = 15 m, L_{max} = 500 m, $N_{v,max}$ = 12 (corresponding to the maximum observed value) and F = 1.25 will be adopted. The distance to the nearest exploitation (*i.e.* L in Eq. 2b) is taken as the vertical distance from the bottom of the geologic layer of interest to the shallowest mined zone. It is noted L_2 when referring to the distance needed to compute the damage to Turonian marls and L_3 when referring to that relating to the tertiary sands and Cretaceous chalks (Fig. 3). These distances to the nearest exploitations can be computed from the geological model of Kaufmann and Martin (2008) and from the depth of the shallowest exploitations.

The permeability of the damaged geological unit is then computed from the damage index as

$$K = \exp\left((1-D)\log(K_{init}) + D\log(K_{max})\right) \qquad (4)$$

where K refers to K_1 when computing the permeability of the damaged Carboniferous bedrock, K refers to K_2 when computing that of the damaged Turonian marls, and K refers to K_3 when computing the permeability of the damaged Tertiary/Cretaceous cover. K_{init} [m/s] is the natural permeability of the geological layer and K_{max} [m/s] is its maximum permeability once it has been damaged. K_{max} is arbitrarily taken equal to 100 × K_{init}. Initial values of permeability were taken as 10^{-7} m/s, 10^{-10} m/s, and 10^{-9} m/s for the upper chalk

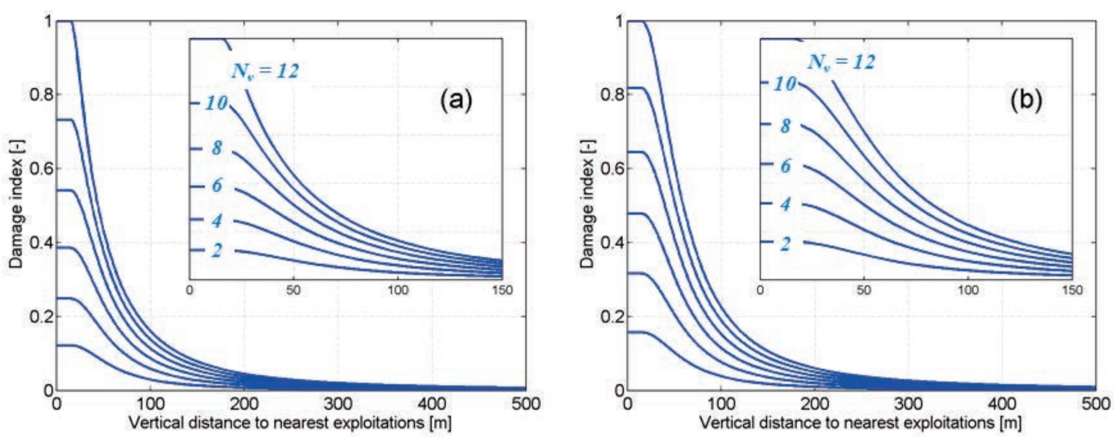

Fig. 4 *Damage function corresponding to L_{min} = 15 m, L_{max} = 500 m, $N_{v,max}$ =12. (a) F = 1.25. (b) F = 2.5.*

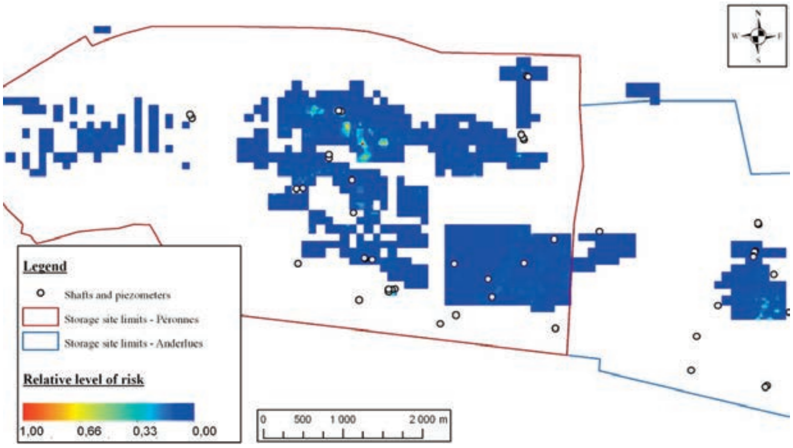

Fig. 5 *Relative level of risk of gas surface emanations*

and tertiary units, the Turonian marls, and the Carboniferous bedrock, respectively.

Target component

The target component is quantified as the distance to the nearest housings. It is directly computed within the GIS using a numerical version of the topographic map of the area.

Results

The global level of risk is directly computed as the ratio of the hydraulic conductance of the overburden C_{tot} to the distance to the nearest housings. Fig. 5 shows the results of the analysis. The pixel size is adjusted here on that of the geological model (30 × 30 m). The values are normalized so that they range from 0 to 1.

Several "hot spots" appear on the map. It can be seen that they do not directly correspond to heavily mined areas or to very shallow exploitations. Indeed, in Anderlues, while the exploitations are generally relatively deep, the overburden is usually much thinner and Turonian marls are not necessarily present over the whole storage site. As a result, zones of higher risk also appear in Anderlues. These hot-spots on the map could be selected as potential site for the installation of new piezometers.

Conclusions

A methodology has been developed in order to locate new piezometers to monitor surface gas emanations from former underground gas storage sites. The method uses regional-scale geological cross-sections to identify the number of exploited coal seams and estimate their depth. A damage index is computed in order to quantify the degradation of subsurface permeability. The methodology applied to the sites of Péronnes-lez-Binche and Anderlues, in Belgium. The sites are abandoned coal mines that have been used for gas storage for a period of about 20 years.

While the methodology has been applied to storage sites for natural gas, it is also largely applicable in the framework of carbon dioxide sequestration projects. The methodology is also applicable to abandoned mines undergoing flooding, the rising groundwater level pushing the residual gas towards upper mined voids and favouring gas migration towards the surface.

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