Geotechnical and environmental impacts on the surface of the water rising in French underground coal mines after closure

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Abstract: The water rising in underground coal mines, after their closure and, therefore, to the interruption of the dewatering pumping, may have non-negligible impacts of various types on the surface and on the environment. In the scope of numerous studies conducted in the various French coal basins, INERIS developed a study method to define the residual mining risks, as well as their potential impacts on the environment, resulting from the definitive closure of the coal mines. Amongst the main consequences of the flooding of mines on the environment, we will more especially deal with the impacts of the water rising on the stability conditions of the surface (risk of subsidence restoration or elevation of the ground; risk of collapse ...) and with the risks of gas emissions to the surface or even accumulations in places not or badly ventilated. The various phenomena and mechanisms that are at stake and the compensatory measures the most currently implemented to reduce and/or manage these risks are briefly depicted. Finally, a mathematical model to efficiently manage mine gas resource after the mine closure, while guaranteeing the safety of people and facilities and the protection of the environment, is more thoroughly detailed.

1 INTRODUCTION

The definitive closure of an underground mine generally gives rise to the interruption of the dewatering pumping. The resulting rise of the water level within the mine may have non-negligible effects of various types on the surface. The major effects and associated risks are as follows:

1. Potential impacts on the quality of underground and surface waters and the appearance of water outlets more or less diffuse at locations that are a priori not always easy to predict (Bour et al., 1999).
2. The stability conditions of the mining works with an outlet at the surface, such as the shafts and adits, may be significantly and unfavourably modified in the presence of water. The treatment of these openings is generally necessary, through the implementation of a self-bearing concrete plug at the head or within the structures for example (Wojtkowiak & Didier, 1999), to guarantee the safety of people and property in the direct vicinity of the mine.
3. Land movements may appear at the surface consecutively to the instabilities of the bottom works and damage the frame and infrastructures.
4. Mine gas releases may also take place at the surface and the risks linked to the accumulation of these gases in confined areas and premises that are not or poorly ventilated are far from being negligible.

Based on the extent and magnitude of the geotechnical and environmental impacts on the surface of the flooding of the underground mine works, in this article we will only analyse the two last above-mentioned points, i.e. impacts of water rising on the stability of the surface and mine gas releases.

Firstly, we will deal with the various mechanisms that can result from the flooding of the mines and their potential effects on the surface. Based on the studies conducted by INERIS on behalf of Charbonnages de France in the various French coal basins, we will study the nature of these impacts and, if applicable, its importance vis-à-vis the safety of people and surface facilities. Then, we will briefly present the compensatory measures the most commonly implemented to reduce risks linked to mine gas emissions to the surface. One of these measures consists in exploiting the mine gas resource and therefore reducing the methane emissions to the atmosphere. The optimisation and the search for profitability of such an operation, while guaranteeing the safety of people and surface facilities and the protection of the environment, lead us to develop a mathematical model that is presented in this document and that makes it possible to forecast the behaviour of the gas reservoir and ensure the perenniality of its exploitation.

2 GEOTECHNICAL IMPACTS OF THE WATER RISING

After underground mines are closed, once the shafts and adits with an outlet at the surface are treated to guarantee the safety of people and property in their direct vicinity, problems linked to the long-term stability of the undermined land arise.

The rising of the underground water, resulting from the interruption of the dewatering pumping is one of the factors liable to modify the long-term stability conditions of the mining works, of the overburden disturbed by the works and, therefore of the surface of the land. Indeed, a change in the hydraulic environment may have a major influence on the state of the stress forces within the massif as well as on the mechanical characteristics of the rock mass.

Studies conducted in various coal basins made it possible to define the type of impact of the water rising on the stability of the surface and, if applicable, to translate its importance in terms of damage to the buildings.

2. 1 Hydraulic consequences of underground works

While the mine is still in operation, fractures that already exist within the massif slightly grow vertically from the works and add on to those induced by the mining operations. All these fractures play a draining role that grants permeability coefficients to the influence volume of the mining works higher than those of the sectors located outside the area disturbed by the mine. Water from the overlying aquiferous formations may therefore flow in the direction of the mining works thus often requiring the implementation of a dewatering pumping system while the mine is in activity. The pumping gradually drives back the aquifers influenced by the activity of the mine.A desaturation of the massif complements this effect in the direct environment of the mine (close field), whether as regards the rock matrix or the network of fractures it is subject to.

2. 2 Modifications of the mechanical properties of the rock mass

The state of the geological medium may be characterised by the values of a certain number of state variables pertaining to the various categories of physical phenomena, at a given moment. These phenomena are hydraulic, mechanical, thermal and chemical. This study is limited to the two first aspects (Fig.1).

The role of water on the mechanical behaviour of a massif is mainly limited to the action of the volume forces (Archimède's principle and outflow forces) and of the interstitial pressure. Each one of these forces is linked to the hydraulic load that is a function of the flooding level of the massif (piezometric altitude of the aquifers).From a mechanical standpoint, the action of water on a massif as several consequences.

- A redistribution of the stress within the massif: the transitory phase of the water rising, that is often the phase with the most unfavourable conditions for the stability of the massif, must be distinguished from the full flooding phase that generally leads to the instalment of a new hydraulic and mechanical equilibrium within the massif.
- A reduction of the mechanical characteristics of the rock mass: although it is systematic, it varies in amplitude according to the type of materials. The more the water saturation degree is low before the flooding, the more the reduction of the geomechanical characteristics of the massif will be high. For example, we note that the ratio between the uniaxial compressive strength of a dry material and that of the same material saturated in water varies from 1. 2 to 2. 5 for the carboniferous sandstones and shales, that it is more or less equal to 2 for the iron ore from the Lorraine area, and may reach 4 for certain chalks from the North of France.

2. 3 Consequences of the water rise on the surface stability

The interruption of the dewatering pumping when mines are closed will gradually give rise to a rising of the underground water that will fill residual voids that result from the mining activity until a new hydraulic and hydrogeological equilibrium is achieved.

In this case, we must plan whether or not the stability conditions of the former mining works and of the overburden that existed before the rise of the water might be significantly modified and have repercussions on the stability of the surface (subsidence restoration,local or generalised collapsing...) during the flooding.

a) Case of infrastructure mining works

For the mining shafts that were backfilled, the transitory flooding phase may give rise to phenomena with effects at the surface under certain conditions (untamping of the rocks, breakage of the shaft walling, breakage of the surrounding rock...). By taking into account the influence of numerous factors in favour of the stability of the rocks such as their high granulometry or the "silo effect", it however appears that the probability of occurrence of such phenomena is low. Anyway, after the stabilisation of the water level, the risks of impact on the surface linked to the flooding become negligible or even nil for these works.

Considering the geological and mining contexts of the French coal basins, the noxious influence of the rising of the underground water on the stability of the adits can only be felt in the event of adits close to the surface (less than twenty metres). Under these conditions, the influence of water may therefore be embodied by:

- a reduction of the mechanical properties of the overburden and of the adit supporting elements,
- a reduction of the slope angle of the caving material cones consecutively to local instabilities of the roof of the adits whether reactivated or initiated by the water rising,
- the influence of the hydraulic pressure.

For adits that are close to the surface, the major risk is linked to the degradation of the mechanical properties of their supporting elements in the presence of water, which may lead to a crown-type breakage, or a further collapsing of the roof. However, after the flooding, the alteration phenomena, that may lead to a reduction of their mechanical characteristics, are considerably slowed down due to the absence of oxygen required to any alteration process.

b) The total mining works

Amongst the various types of total mining works (backfilled, caved in or drawn off longwall face), certain are more liable than others to give rise to surface effects when the underground water rises: this is the case of the backfilled sloped longwall faces. An untamping of the rocks may take place if they are subject to three simultaneous conditions (Fig. 2). In this specific configuration, the empty volume created by the untamping of the rocks may give rise to subsidence elevations liable to open up at the surface (Fig. 3) or a restoration of surface subsidence (Fig. 4).

Forecasts concerning the magnitude of the effects on the surface of such mechanisms were performed thanks to the SUBSID software, developed by the INERIS (Aissaoui, 1999), applied to the former backfilled sloped works of the North and Pas-de-Calais coal basin. The calculations were conducted based on the very pessimistic assumption of a systematic untamping of the rocks consecutively to the water rising. Therefore, we demonstrated that the possible subsidence restoration is negligible and may at the most slightly damage the very long buildings (over one hundred metres long all in one piece), and only if the mining works are located at a depth inferior to 50 m.

Considering the configuration of the backfilled sloped works in the basin of the North and Pas-de-Calais and the type and thickness of the overburden, we also highlighted the fact that the risk of subsidence elevation should be excluded.

c) Partial mining works

The major instability risks are linked to the partial mining works referred to as mining works by rooms and abandoned pillars (Vinkler & Piguet,1999). The alteration of the mechanical characteristics and gradual distortions that affect the various layers, in particular those of the roof, and the pillars have sometimes resulted in the failure of former works several dozen years after they were abandoned.

To this regard, the action of the water is unfavourable to their stability in the short term, as it may give rise to a collapse or subsidence. On the contrary, in the long term, once the layers have returned to their initial piezometric level, no underground external factor can influence the stability of the massif. However, when the land is sensitive to creep that the flooding can reactivate, the situation may change over several years until it is stabilised or until instability is triggered.

2. 4 Elevation of the topographical surface

In certain foreign coal basins, the rising of the underground water is accompanied by an elevation of the surface in the area influenced by the former underground mining works (Bekendam & Pöttgens, 1995). The mechanisms at the origin of this phenomenon still form the subject of studies, however, they seem to be linked to a reduction of the effective stress. In any case, the amplitude of the elevation measured at a given point is much lower than the amplitude of the subsidence supported by the same point during the mining activity. The elevation only represents several percent of the amplitude of the total subsidence. Furthermore, this elevation is gradual and concerns larger areas comparable to those of the subsidence basins. Therefore, there is not much chance that this type of elevation will damage the frame and infrastructures on the surface. Indeed, damage is essentially linked to the horizontal deformation of the ground that is very low in this case.

The levelling measurements performed in several French coal basins that are currently being flooded, will constitute a knowledge and database unique in France to further detail the phenomenon in terms of amplitude and duration, as well as the mechanism(s) at the origin of this elevation.

2. 5. Conclusions

In most of the studied total mining works, the effects on the surface linked to the water rising are in fact only a restoration of land movements due to the reactivation of mechanisms already initiated by and during the underground mining activity. Most of the time, their amplitude and duration are extremely moderate. Furthermore, the fact that most of the risks of impact on the stability of the surface are much higher during the transitory phase of the flooding, should be highlighted. New mechanical balance conditions are set within the undermined massif with a return to a hydraulic and hydrogeological balance of the aquifers. Finally, knowledge as regards the role that the interstitial pressure plays on the long term behaviour of the rocks is still very poor. This partly explains why the hydromechanical coupling is only slightly or even not at all taken into account in the numerical modelling of the behaviour of the underground works in fractured rock massifs.

3 RISKS AND PRECAUTIONARY MEASURES LINKED TO GASES IN CLOSED MINES

3. 1 Firedamp accumulation mechanisms and gas emission to the surface

After the closure of a coal mine, firedamp emissions can stop in certain cases but some gas remains in the void spaces of the underground mine (mining works, fractures and cracks of the rock mass…).

Gas emissions can also continue for a while after the closure. However, the gas emissions can stop with the flooding of coal layers, up to several meters above the coal seams. Therefore, the gas accumulated could migrate to the surface if the pressure within the reservoir is superior to the atmospheric pressure at the surface.

This difference of pressure between the reservoir and the surface may be caused by:

1. an increase of the pressure inside the reservoir with :
- the water rising within the underground void spaces that compress the gas,
- the gas firedamp desorption from the coal in place;

2. the decrease of the atmospheric pressure due to meteorological depressions.

Furthermore, all these possible causes of gas emissions can take place at the same time. Gas then can migrate to the surface :

1. in a privileged manner through communication works between the mine and the surface (old shafts, adits...) ;
2. through the overburden itself.

3. 2. Type of risk linked to the firedamp

The firedamp in the mining caviting and migrating to the surface can cause two risks:

- an inflammation risk, because methane constitutes a flammable mixture with air in certain proportions (from 5 to 15 %):
- a risk of asphyxia, because firedamp accumulates in places not or badly ventilated replacing the atmospheric air.

Several examples of traditional hazardous situations at the origin of incidents or accidents are indicated below:

- punctual and concentrated firedamp emission through a direct communication between the former works and the surface (mining opening, crack...);
- accumulation of gas in confined or semi-confined areas (cellars or basements, even houses or buildings themselves, but also underground networks...);
- restoration of the communication of old works with the atmosphere during drillings or civil engineering works....

3. 3 Prevention and monitoring measures

Beyond the necessity to treat the mining openings, several compensatory measures (treatments) may be implemented to limit the migration of the fire-damp and its accumulation up to explosive contents. Two types of measures may be defined:

- **the passive treatment:** in certain cases, it may be necessary to perform bore holes from the surface to intercept certain high points of the underground reservoir. On the one hand, they make it possible to check the parameters of the gas reservoir : composition and pressure. On the other hand, they can constitute outlets for the gas that can be totally controlled and safe (far from housing areas and fitted with safety devices such as shut-off valves), and can more or less partially replace the non-controlled "natural" outlets.
- **the active treatment:** the underground reservoir can be in depression with the atmosphere by extracting the gas. If surface communications are sufficiently tight, it is therefore possible to reach very low absolute pressures from 0. 3 to 0. 5 bar. The extent of influence of a drainage borehole can be very large: several km2 and even hundreds of km2.

3. 4. Drainage installations

In French coal basins, gas drainage installations on abandoned mines appeared in response to the following objectives.

- **Safety:** the mine gas drainage can be an efficient way of controling gas emissions to the surface.
- **A contribution to the protection of the environment,** by the reduction of the methane emissions to the atmosphere.
- **Energy recovery,** with the marketing of the gas.

Facing the requirements to extract and market such a resource, modelling tools are needed to forecast or evaluate the behaviour of these gas reservoirs. As they did not exist, a mathematical model was therefore developed to appreciate the capability of the reservoir to supply gas for a given period, and to characterise the operating conditions that will guarantee an optimum production.

a) Characteristics of a mine gas reservoir

b) A firedamp reservoir is the entire volume destabilized by an old mining (a district, a main level, or a mine), made tight from the outside and whose voids spaces grew rich out of methane.It is often about a large-sized deposit, whose gross volume can reach several tens of million cubic meters. Contrary to a conventional reservoir, volume is not materialized by defined walls or external immediate strata. Useful volume corresponds then to the volume of the cavities and spaces due to the cracking and the porosity of remaining coal as well as to residual volumes of the galleries and the underground workings. This volume does not represent the mine gas reserve since the methane is at the same time stored in a free form in the pores and cracks of the coal and rock matrix, and under an adsorbed form on the coal surface within the micropore structure. In case of communication with a water table, the reservoir volume decreases progressively with the rising of water.

b) General behaviour of the reservoir

In extracting mode, the outgoing flow of drained gas is generally higher than the incoming flows of gas within the reservoir. Then, the reservoir pressure decreases, which increases parasitic air intake in the reservoir. The gas drainage can thus be continued until a certain absolute reservoir pressure : from a pressure level, the incoming flow of air involves in general a too important reduction in the methane content of the drained gas, which must be at least 50% to 65%. Periods during which the extraction is stopped must thus be programmed in order to reload the reservoir with methane.The absolute pressure within the reservoir and the methane content of the drained gas are the two principal parameters governing the behaviour of the reservoir.

The figure 6 presents, for a real site, the evolution of the pressure within the reservoirs and the methane content of the mine drainage.

c) Reservoir modelling

A modelling tool was developed to forecast the behaviour of the reservoir (pressure within the reservoir and methane content in the collected gas) according to the extracted gas quantities.

Due to the coal structure, that may be assimilated to an assembly of grains drained by a network of cracks, the study of mine gas storage takes place at two levels:

- as regards the material grain where the adsorption, desorption and diffusion phenomena take place,
- as regards the network of cracks in which the "free" gas flows out according to the permeability .

Therefore, the physical laws governing the gas circulation in the reservoir are complex:

- firedamp desorption (Langmuir law...),
- mine gas diffusion within a coal massif (Fick law...),
- gas outflow in porous and permeable media (Darcy law...),
- circulation of fluids in mining infrastructure works and gas pipes.

The approach consisted in comparing the reservoir to a total volume whose pressure varies with the outgoing flow of mine drainage gas and the total incoming flow due to the firedamp desorption and the air intake.The law of perfect gases was retained to connect the quantity of gas contained in the reservoir and the pressure in this one. For relatively steady conditions, it is then possible to calculate the total incoming flow of gas (firedamp desorption plus air intake) and the volume of the reservoir.

The modelling suggested was implemented using experimental data from two reservoirs currently exploited and located in the Lorraine basin in the East of France.The model was evaluated on the results of forcasts based on past experimental data (Fig. 6). The results prove very satisfactory with, for the modelled variables (pressure and content methane), an absolute average error between the observed and predicted values lower than 10%. Discrepancies between observed and predicted values can also be observed during the stop of the extraction : the absence of gas circulation makes the measurements much less representative of the gas reservoir. Although the gas sources localization remains difficult, one can indeed easily admit that gas drainage, air intake and desorption can take place in three distinct points in the reservoir. The measurements of methane content is made at the level surface, on the gas extraction installation. Due to the large size of the deposit, the measurements representativeness remains relative.

3. 5. Results

The pressure of the reservoir and the methane content of the extracted gas have been modelled according to the quantities of extracted gas. The periodic calculation of the model parameters with recent exploitation data will allow a follow-up of the site characteristics in terms of reservoir volume and desorption potential.

Lastly, modelling must also be employed in order to optimize the phases between the stops and the extraction, or the mine drainage gas flowrate.

The model thus developed and validated on two real cases could be used thereafter on other sites and will constitute a true tool of optimization and industrial management of a firedamp reservoir.

4. CONCLUSION

Based on numerous studies performed in the various French coal basins, the INERIS developed a comprehensive method to identify and analyse the risks linked to the definitive closure of underground mining works, especially by integrating the consequences on the surface of the water rising within the former mining works. Grounded on this analysis, compensatory measures to reduce these risks may be defined and optimised whether from the technical or economic standpoint, while guaranteeing the safety of people and property in the long term. Over time, the implementation of measurement and monitoring devices in the closed mining basins should provide data indispensable to compare the forecast with the actual behaviour of the mining works.

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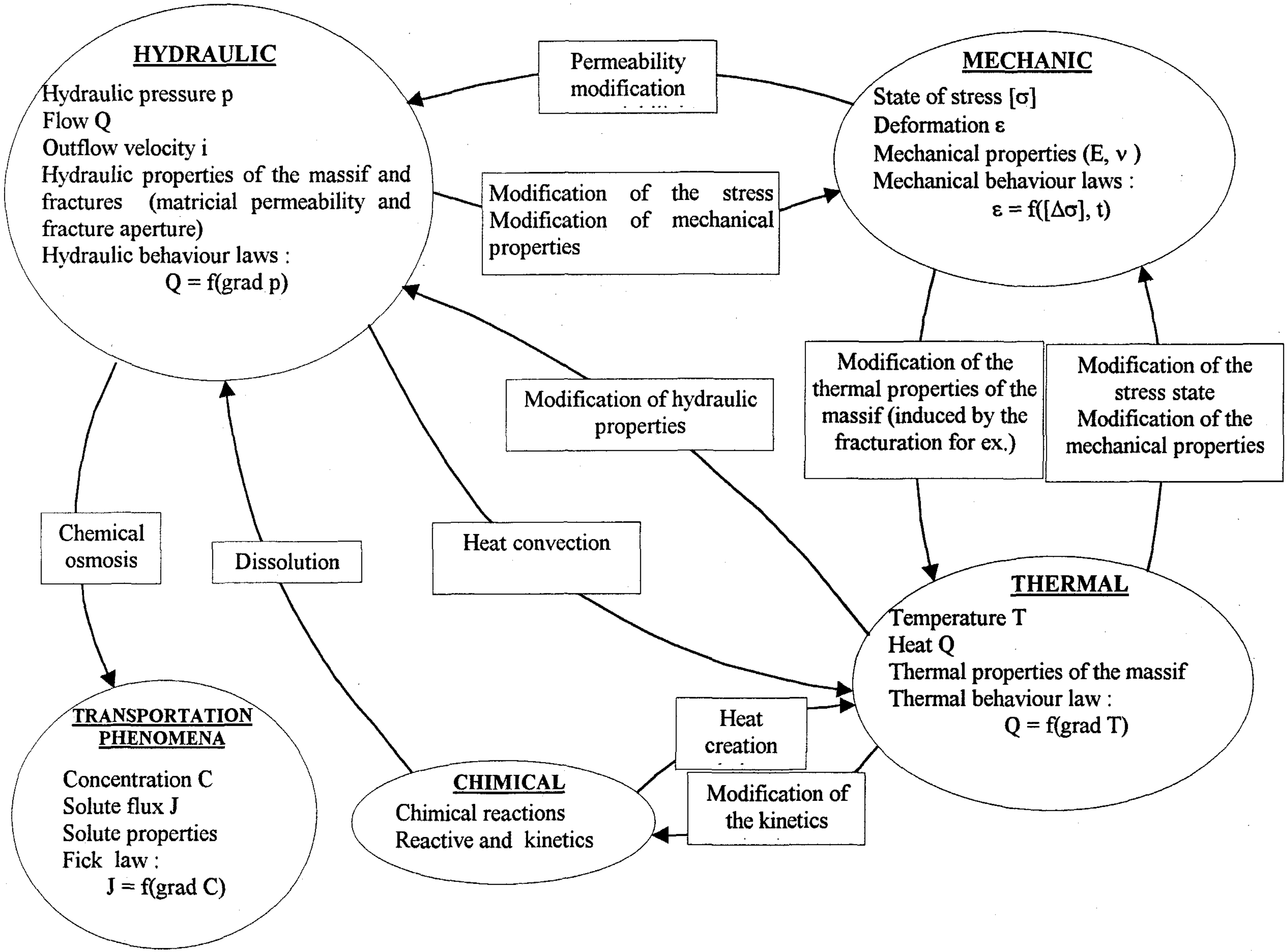
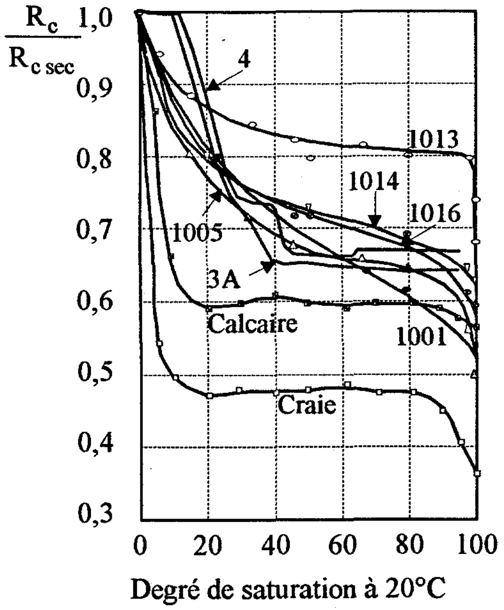

HYDRAULIC
Hydraulic pressure p
Flow Q
Outflow velocity i
Hydraulic properties of the massif and fractures (matricial permeability and fracture aperture)
Hydraulic behaviour laws :
Q = f(grad p)
Permeability modification
MECHANIC
State of stress [σ]
Deformation ε
Mechanical properties (E, ν)
Mechanical behaviour laws :
ε = f([Δσ], t)
Modification of the stress Modification of mechanical properties
Modification of hydraulic properties
Modification of the thermal properties of the massif (induced by the fracturation for ex.)
Modification of the stress state Modification of the mechanical properties
Chemical osmosis
Dissolution
Heat convection
THERMAL
Temperature T
Heat Q
Thermal properties of the massif
Thermal behaviour law :
Q = f(grad T)
TRANSPORTATION PHENOMENA
Concentration C
Solute flux J
Solute properties
Fick law :
J = f(grad C)
CHIMICAL
Chemical reactions
Reactive and kinetics
Heat creation
Modification of the kinetics



1001 : quartzite (Wiid, 1967)
1005 à 1016 : différents grès (Wiid, 1967)
3A et 4 : différents grès (Ojo et Brook, 1990)
Calcaire : calcaire grossier du Bassin Parisien (Watelet, 1996)
Craie : craie du Bassin Parisien (Watelet, 1996)

Figure :

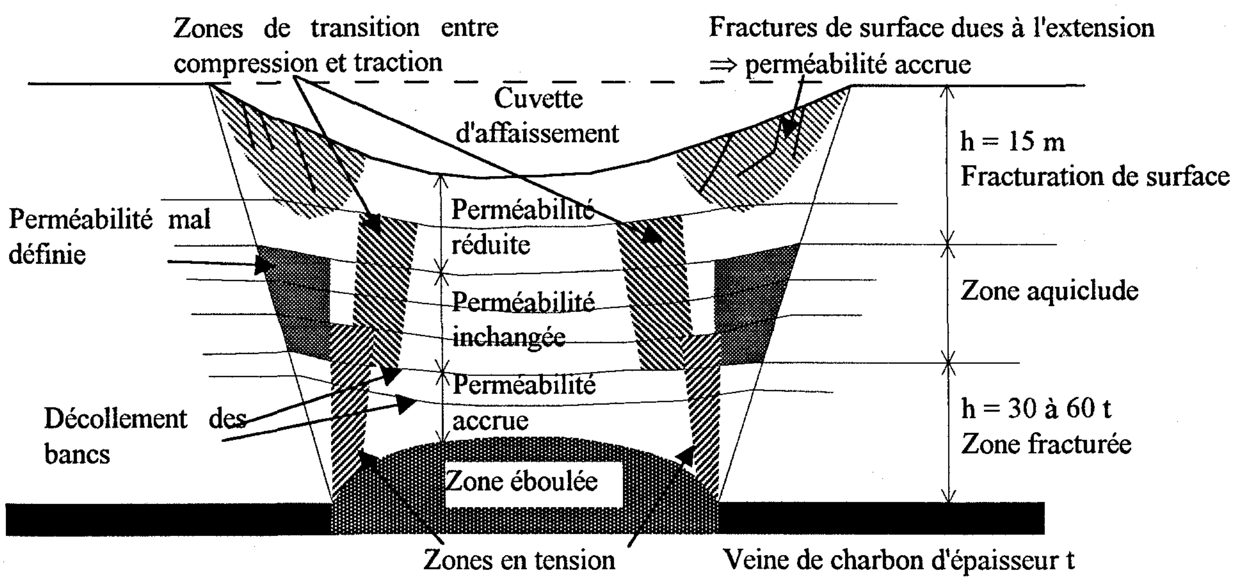
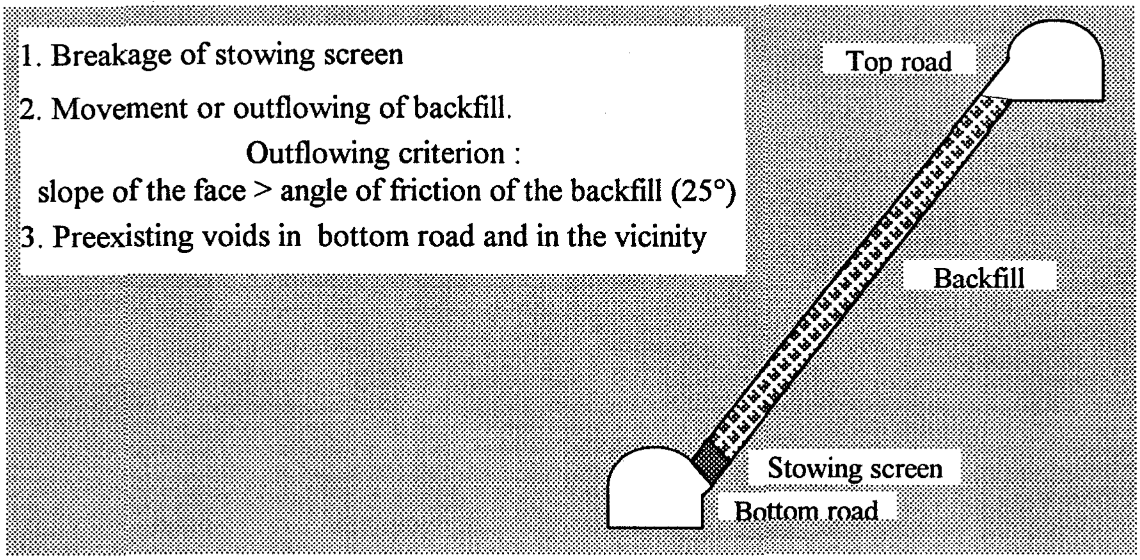
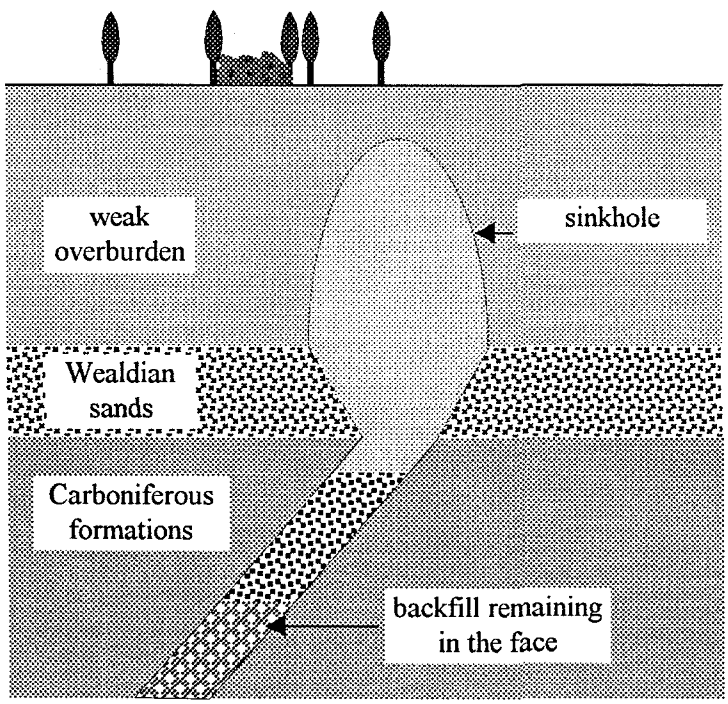
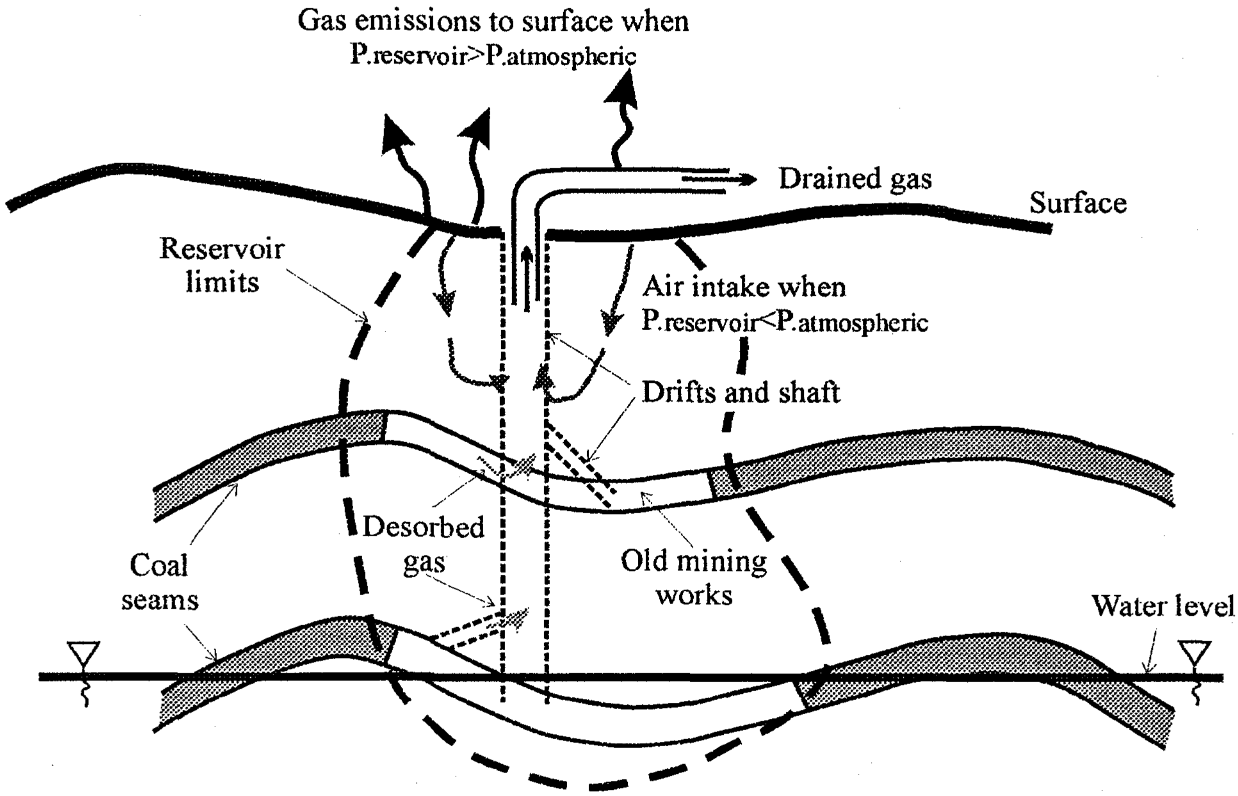
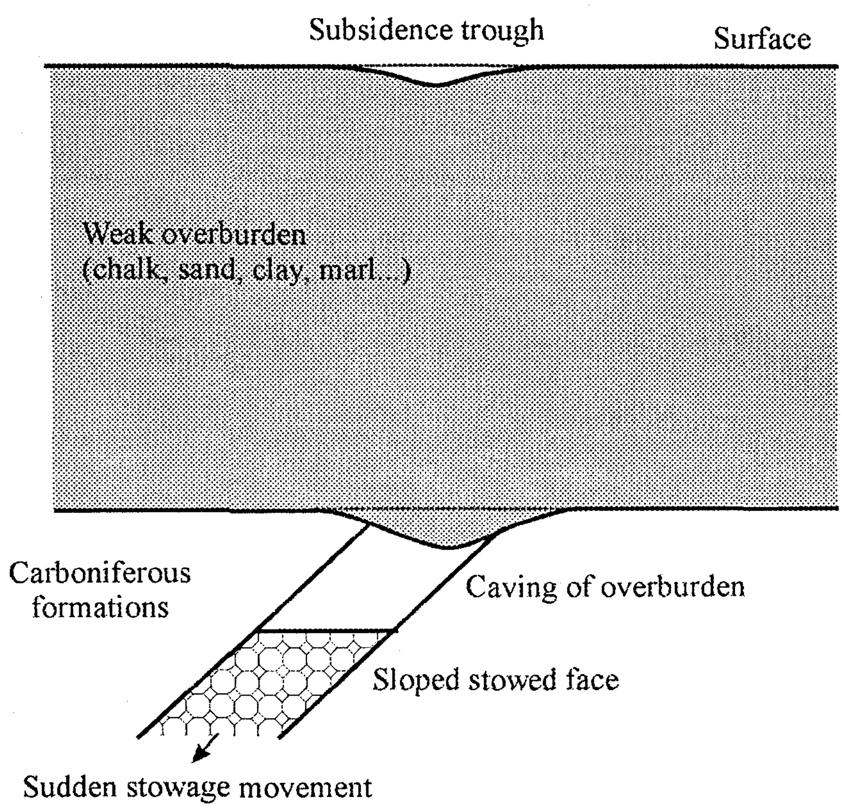


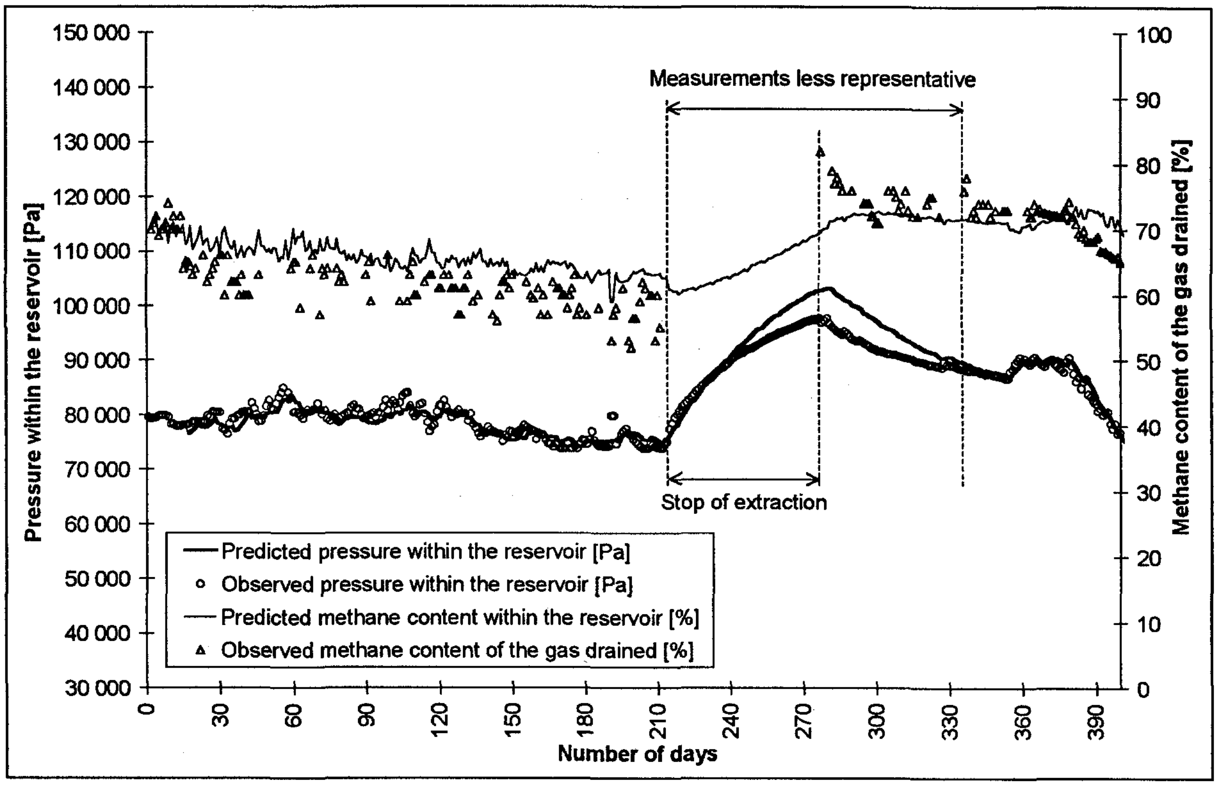
Figure :


1. Breakage of stowing screen
2. Movement or outflowing of backfill.
Outflowing criterion :
slope of the face > angle of friction of the backfill (25°)
3. Preexisting voids in bottom road and in the vicinity
Top road
Backfill
Stowing screen
Bottom road


weak overburden
sinkhole
Wealdian sands
Carboniferous formations
backfill remaining in the face


Gas emissions to surface when
P.reservoir>P.atmospheric
Drained gas
Surface
Reservoir
limits
Air intake when
P.reservoir<P.atmospheric
Drifts and shaft
Desorbed
gas
Coal
seams
Old mining
works
Water level


Subsidence trough
Surface
Weak overburden
(chalk, sand, clay, marl...)
Carboniferous
formations
Caving of overburden
Sloped stowed face
Sudden stowage movement


Measurements less representative
Stop of extraction
Predicted pressure within the reservoir [Pa]
Observed pressure within the reservoir [Pa]
Predicted methane content within the reservoir [%]
Observed methane content of the gas drained [%]
Pressure within the reservoir [Pa]
Methane content of the gas drained [%]
Number of days
150 000
140 000
130 000
120 000
110 000
100 000
90 000
80 000
70 000
60 000
50 000
40 000
30 000
100
90
80
70
60
50
40
30
20
10
0
0
30
60
90
120
150
180
210
240
270
300
330
360
390