HANDBOOK

2019 / Ineris DRS-19-178745-02411A

Post-Mining Hazard Evaluation and Mapping in France

INERIS

controlling risks
for sustainable development

This methodological handbook was developed at the request of the General Directorate for Risk Prevention (DGPR), a division of the French Ministry for the Ecological and Inclusive Transition.

It was created under the direction of the French National Institute for Industrial Environment and Risks (Ineris) as part of its missions in support of the Ministry.

This document is also based on a previous handbook on developing Mining Risk Prevention Plans, which was created under the coordination and scientific direction of Ineris[1].

This document was verified by the Ground and Underground Office (B3S) of the DGPR with the support of GEODERIS and the Post-Mining Divisions.

Directed by:

Christian Franck and Romuald Salmon (Ineris)

Authors:

Christian Franck, Romuald Salmon, Christophe Didier, Yves Paquette and Zbigniew Pokryszka (Ineris)

Reading committee:

- Olivier Astier, Valérie Michaut (B3S)
- Aline Lombard, Sébastien Thiery (Cerema)
- Rafik Hadadou (GEODERIS)
- Pascale Hanocq (Post-Mining Division East)
- Dominique Leroy (Post-Mining Division West)
- Jehan Giroud (Post-Mining Division South)

all contributed their experience and support at various stages in the development of this document.

The present English version is a translation of the original *Guide Evaluation des aléas miniers*, written in French, which remains ultimately the reference documentation.

1 - "*L'élaboration des Plans de Prévention des Risques Miniers. Guide Méthodologique. Volet technique relatif à l'évaluation de l'aléa. Les risques de mouvements de terrain, d'inondations et d'émissions de gaz de mine.*" INERIS Report DRS-06-51198/R01, 05/04/2006.

Table of contents

1 INTRODUCTION

This handbook discusses the hazards that can affect territories where former mining operations took place.

The hazard study, and the maps associated with it, are essential steps in the efforts to manage the risks those former mines can generate and to develop those territories sustainably.

The objective is to map the areas where hazards exist and to evaluate their severity in order to determine the risk for existing stakes and the possibilities of construction or development in terms of land planning.

This key technical step enables stakeholders to develop post-mining risk management procedures, allowing local authorities to better understand and adapt to potentially dangerous phenomena and helping land planners better understand the conditions of constructability.

This handbook provides information on post-mining phenomena, the experience feedback that has been established thus far and indications on the parameters to be considered when evaluating, classifying and mapping a hazard.

This document draws extensively from the handbook published in 2006 under the coordination and scientific direction of Ineris [1], for which it has created an abridged version dedicated exclusively to hazard evaluation.

It includes newly added information on additional phenomena: discontinuous subsidence, crevices and the specific mechanisms of overheating in mine tailings.

The procedure for evaluating the hazard of localized collapses was substantially modified, based on post-implementation feedback from GEODERIS [2] and on feedback related to observed disturbances [5].

The evaluation process for mine gas was also substantially modified in light of the advances and conclusions made in the handbook on this hazard published by Ineris in 2016 [6].

However, this handbook does not discuss the environmental impact or ionizing radiation emissions from mining activities. The potentially dangerous phenomena associated with these issues have a specific approach for evaluating and managing risk that is different from the approach taken via the hazard studies described in the post-mining risk management handbook [7]**.**

2 BACKGROUND OF POST-MINING IN FRANCE

Like many other European countries, France has a long-held mining tradition. The extraction and commercialization of raw materials in its subsoil was a decisive contributor to France's development as an industrial power.

In French territory, the earliest evidence of underground mineral resource exploitation (ancient flint mines, salt springs) dates back to the Neolithic age (5^{th} to 3^{rd} millennium B.C.E.). Even before the Roman occupation, the Celts and then the Gallics regularly mined gold and tin (1^{st} millennium B.C.E.). But it was during the Gallo-Roman era that mining truly began to flourish, when silver, lead, copper and iron were all sought out and exploited in turn. At that time, mining activity took place in a multitude of small, local mines scattered throughout the territory (1^{st} and 2^{nd} centuries).

After the fall of the Roman Empire, mining exploration and extraction continued at a slower pace for nearly a thousand years. Under the influence of Central Europe, and in order to meet the growing economic needs resulting from the increasing population and political stabilization, mine prospecting and exploitation began to proliferate once more (11^{th} – 13^{th} centuries). It was during this time that the first coal mining began in the regions of Hérault, Provence and Sarre.

But it was the industrial revolution (17^{th} – 18^{th} centuries) that became the crucial impetus for the development of mining in France. Technological advances helped transform what had previously been essentially an artisan activity into an industrial operation. In addition to the large mining basins (coal, iron, salt, etc.) that would greatly contribute to the wealth of the national economy, the early 19^{th} century also saw a wide diversification of materials being sought and exploited (e.g., oil, manganese, fluorite, zinc).

Mining continued to flourish in mainland France during the first half of the 20^{th} century, primarily driven by the two world wars.

In the aftermath of World War II, the national effort to rebuild the country and reduce France's energy dependency encouraged a mining revival. Coal and lignite production rapidly increased, reaching 60 million tons in 1958, a record year.

Various economic factors, the development of the use of hydrocarbons in energy production, competition from foreign deposits and the depletion of some French deposits gradually led to the decline of mining in France. This decline began in the early 1960s for coal and iron and the early 1980s for other substances, then accelerated since the early 1990s.

The last iron mine closed down in 1995, and the last uranium mining stopped in 2001. Potash mining in Alsace ended in 2003, and the last coal was mined in 2004. The mining industries that remain active in mainland France[2], aside from deep geothermal deposits, are salt extraction via underground mines or dissolution, bauxite mining and hydrocarbon exploitation.

At the end of the 1990s, in response to various phenomena or nuisances occurring in the areas surrounding former mining sites, including ground movements that caused disturbances in nearby dwellings (mine collapses in Lorraine in 1996, 1997 and 1998 affected over one hundred homes), the French government began to develop tools for managing the consequences of mining cessation in a phase known as "post-mining."

Furthermore, former mining and industrial areas, which have undergone changes as the mines and related industries have gradually shut down, present serious challenges for planning and developing the layout of the territory, which may be faced with potential risks caused by mining.

Therefore, it is necessary to identify and locate, as precisely as possible, the risks and nuisances that are likely to persist after mining activity has ended in order to be able to determine the possibilities for land development and the operational measures best suited to each context.

Different tools exist to reach this goal. They are presented in the post-mining risk management handbook [7]. One of them is called "hazard study" and is presented in details in the present handbook.

2 - Nickel mining is still very active in New Caledonia. Likewise, there are still substantial gold mines in Guyana.

3 KEY CONCEPTS AND PRINCIPLES OF HAZARD EVALUATION

3.1 What is a hazard?

"Hazard" is a commonly used term in risk prevention. It means the probability that a phenomenon—in this case one caused by mining—will occur on a site, during the course of a reference period, reaching a qualifiable or quantifiable intensity. Hazard characterization is traditionally based on the intersection of the predicted intensity of the phenomenon and its probability of occurrence.

In terms of risk prevention, a reference period means a duration of several decades or even several hundred years, used to determine an order of magnitude. Thus, it is necessary to integrate in the analysis the inevitable deterioration of old mines over time and the evolution of the materials and effluents (gas, water) that issue from them.

A phenomenon's **intensity** corresponds to the extent of the disturbances, aftereffects or nuisances that are likely to result from that potential phenomenon. This integrates not only the concept of the magnitude of potential events (e.g., crater size and depth, water level, nature and content of gas emissions), but also their potential effects on people and goods.

In this context, the concept of **probability of occurrence** refers to how sensitive a site is to being affected by a phenomenon. Regardless of what type of mining-induced event is anticipated, the complexity of mechanisms, the heterogeneous nature of the natural surroundings, the incompleteness of the available information and the fact that numerous disturbances, aftereffects or nuisances are not repetitive all demonstrate that it is generally impossible to reason in terms of a probabilistic quantitative approach. Therefore, we use a qualitative classification that characterizes a site's **predisposition** to be affected by a given phenomenon. This is the concept that will be used in this document.

3.2 How to evaluate and classify a hazard

A hazard is thus the result of the intersection between intensity and predisposition. The principle of hazard qualification consists of combining the criteria used to characterize first the intensity class of a potential phenomenon and then its predisposition class.

3.2.1. Qualifying intensity classes

Intensity classes are necessary to categorize potential damages or nuisances based on the nature of the phenomena.

The approach to evaluating the intensity of a phenomenon consists of identifying the most representative physical parameters in order to characterize the consequences of potential dangerous events. Thus, one can choose whether to focus on criteria related to the size of collapse craters, the amplitude of horizontal surface land deformations or the nature, content and flow of gaseous emissions, etc.

Characterizing potential consequences involves referring to the concept of the "severity" of potential events. Severity means the extent of foreseeable consequences to targets that may be present on the surface. This can apply to people (victims) and property (damages).

The number of intensity classes used for analysis may vary based on the context of the study and especially the accuracy and exhaustiveness of the input data.

Hazard studies conducted in the context of mining risk prevention use the following classes to define a phenomenon's intensity: ***very low*** *(rarely used, reserved for phenomena with very low occurrences),* ***low, moderate, high and very high*** *(also rarely used, reserved for devastating events of exceptional intensity).*

3.2.2. Qualifying predisposition classes

Qualification of a predisposition consists of an analysis of the possibility that a phenomenon will appear or manifest on the surface.

This analysis is based first on experiential feedback, meaning past occurrences of disturbances or nuisances on the site being studied or on a similar site.

But a mining site that may not have been the location of known disturbances (some may have been forgotten) may nonetheless feature favorable conditions for a disturbance to occur. Thus, the second approach is to detect these mine configurations by examining the type and configuration of the mining works and their topographical, geological and hydrogeological environment.

In addition, because most of the mines in France are very old, it is very rare to have access to all the documents and plans on works, structures and previous mine disorders. Furthermore, some of these documents and plans contain inaccuracies or are based on references that no longer exist. Because of the uncertainties generated by this incomplete and fragmented information, a predisposition analysis may include a criterion for the presumed presence of mining works and/or structures that may point to the presence of a hazard. Thus, this is a complex approach that requires proven expertise.

The following terminology is used to define a site's predisposition: ***very unlikely*** *(rarely used),* ***unlikely, likely, very likely*****.**

3.2.3. Qualifying hazard classes

Multiple principles, both implicit and explicit, are used to combine qualitative values amongst themselves or to cross reference qualitative and quantitative criteria. These may include techniques that use scoring systems, rankings, multi-criteria classification, etc.

If the two-way table system is selected, use a matrix like the one illustrated as an example in the table below (Table 1), keeping in mind that each site may require adjustments to fit its specific context. Hazard level is evaluated on a case-by-case basis for each site.

The following terminology should be used to qualify the three hazard classes: ***low, medium and high.***

3.3 How to map a hazard

3.3.1. Evaluating the extent of effects on the surface

A hazard map should encompass all surface land that may be subject to the possible effects of phenomena caused by mining activities.

It is essential to account for the possible lateral extension of disturbances or nuisances that originate within underground cavities and spread to the surface.

In fact, past experience shows that instabilities or flow migrations are not limited to areas directly above old mine sites, but may actually spill over, sometimes to large extents, onto land that was not directly exploited with mines.

3.3.2. Including uncertainty factors

The hazard map must include the uncertainties inherent in the plans and information available and in the results of the estimates and models that are necessary for evaluating hazards.

An essential baseline of the hazard study consists of pinpointing any mining works and structures where hazards are likely to occur on a current topographical map. This process may reveal significant uncertainties, especially if the archives are very old or inaccurate, varying in origin or even contradictory. For "flooding" hazards, these maps are often the result of estimates calculated based on hypotheses or the results of an expert opinion.

Table 1: An example of a two-way table for evaluating hazard based on predisposition and intensity

Intensity	Predisposition		
	Unlikely	**Likely**	**Highly likely**
Low	Low	Low	Medium
Moderate	Low	Medium	High
High	Medium	High	High

4 STAGES OF A HAZARD STUDY

A hazard study is conducted in two stages:

- an "information" stage consisting of a description of the mining sites being studied (brief history, geographic and geological environment, form and layout of exploitation, inventory of past disturbances) and the collection and evaluation of archive and land data needed to evaluate the hazard. At the end of this stage, one or more informative maps are produced;
- a hazard evaluation stage that defines, for each phenomenon identified as being relevant to the sites being studied and for each mining configuration, the intensity and predisposition criteria described above and the severity level of the hazard. At the end of this stage, one or more hazard maps are produced based on the number of relevant phenomena and the scope of the territory being studied.

The hazard study report brings these two stages together.

4.1 Geographic scope of a hazard study

The first step is to define the study's scope. A mining sector generally covers territory in multiple municipalities. The hazard maps produced at the end of the study are disseminated to these municipalities; consequently, it is important that the hazard study exhaustively addresses all mining sites and substances in these territories, based on what is known of former mining activities. For example, in the territory of a coal basin, other extractions or explorations (for iron, polymetallic substances, etc.) may also have taken place, but are unknown or even forgotten, and these may have an influence on the development of the territory.

4.2 The information stage

The information stage is absolutely essential, not just to the successful completion of the hazard evaluation stage (i.e., the reliability of the evaluation and hazard maps), but also so it can be properly communicated to local authorities in the territory. It will be easier for the local authorities to accept the evaluation when all available mining information has been taken into consideration and residual uncertainties have been thoroughly identified and explained.

4.2.1. Data collection

4.2.1.1. Researching documents and archives

The first source of information that should be consulted, when it exists (for more recent mines), is the regulatory dossier on abandonment or cessation of mining works established by the mine's operator. This dossier generally contains a vast majority of the information needed to identify and classify hazards.

For orphan mines or old abandoned mines with no dossier, or for those whose dossiers are old and deemed insufficient for evaluating hazards in light of the information they contain, additional research must be done. The same goes for recent exploitations located on territories where the presence of old mines is recorded or presumed: the abandonment dossier established by the last holder of the mining title may not have included all of these old works, and it is important to do additional research.

All of these information sources should be explored. The ones that are most relevant and should always be consulted are the national archives, corporate/company archives, departmental archives or local archives. Archives kept by speleological associations or for the recognition and development of underground spaces (mine museums), geological survey underground database, geological maps, specialized publications can also provide additional information that should not be overlooked.

Old monographs, specialized text and publications, and dissertations may also provide accurate information; local press archives can offer details on past events.

The objective is to collect the maximum amount of information on the method or methods of exploitation, the precise location of the works, the safety techniques used when closing down the site, important technical data (plans, regulatory inspection reports by mining engineers, applications for funding or authorization to drill mine shafts, etc.) and any knowledge of disturbances that have occurred in the past.

4.2.1.2. Positioning mining plans

During the previous step of researching documents, mining plans can be collected that date from different time periods, from exploration to exploitation and finally to closure of the mine. This is one of the key steps of the information stage: selecting the most reliable, exhaustive and accurate plans and transferring them to a topographic background or orthophotography of the surface, the basis of what will eventually become the informative map. Positioning and geolocating between the bottom and the surface is done by marking mining structures that connect to the surface (shafts, galleries) or other deposits, infrastructures or elements common to both the mining plans and the base map of the surface.

This approach is iterative in that during on-site reconnaissance stages, the structures or infrastructures mentioned on old mining plans can be found and pinpointed more accurately on the map in relation to the surface.

After this iterative process is completed, there will still be an element of uncertainty to the positioning of the plans and structures. This uncertainty is then integrated into the hazard map and constitutes an important element of the map.

Analyzing aerial photographs taken at different time periods may also provide important information on the evolution over time of more recent surface mining installations (1945 and later).

4.2.1.3. On-site reconnaissance

A detailed reconnaissance of the site must always be carried out during the information stage.

It involves tracking down the traces of old surface installations, structures that connect to the surface and mining waste deposits, so that the mining plans can be georeferenced as accurately as possible. In sectors for which there are no plans, and where exploration or exploitation works are presumed to be present based on information in the archives, the discovery of galleries, shafts, deposits, open-pit works, old extractions or other mining structures, and indications of surface movements can point to the presence of underground cavities.

On-site reconnaissance can also reveal traces of disturbances in the vicinity of sectors where underground mining took place, in addition to those mentioned in the archives or reported by local stakeholders. Thus, every effort should be made to identify the geometric characteristics of these disturbances as best as possible in order to link them to a type of phenomenon.

A distinction is made between "evidenced" structures and disturbances (seen on the land with no ambiguity) and "localized" structures and disturbances (mentioned on mining plans or in the archives but not seen on the land).

This localization must be as precise as possible in order to reduce the intrinsic uncertainty of their positioning, and that of the underground mining works, as much as possible.

On-site inspections can also allow the identification of other indicators that are important for analysis, such as topographical indicators, geological indicators (rock outcropping, faults) or hydrogeological indicators (springs, flooded areas).

Where accessibility to underground spaces and safety conditions permit—a circumstance that is becoming increasingly rare as the remaining accessible mines are being closed up—reconnaissance visits to underground structures can help verify or improve the accuracy of existing mining plans, or draw new ones, if necessary. They can also provide important information on the exploitation method or methods used (backfilled areas, superimposed levels, etc.) as well as on the mechanisms and phenomena of instability that are starting to appear inside the mines (deteriorating pillars, blending of the roof, etc.).

For open-pit mines, reconnaissance visits can be used to observe and characterize the condition of rock faces.

This field phase also allows to asswwess the stakes present in the sector of study (dwellings, other occupied buildings, principal infrastructures), although the hazard evaluation is conducted independently of these stakes.

During this phase, one can also collect information from the people who best know the environment surrounding the old mine, including town hall workers, villagers and local experts. These contacts provide an opportunity to collect oral information or even old mining plans that are not available in public archives. The involvement of local authorities is absolutely essential: with proper communication of the objectives of the study, it should instill a climate of trust that encourages the sharing of information.

4.2.2. Informative maps

The informative map is a tool that lists essential information, either known (location of works and structures connecting to the surface, past or present disturbances or nuisances, geological and hydrogeological data [mine water discharge], etc.) or presumed (e.g., uncertain evidence on the surface). It forms the basis for the hazard identification and evaluation map.

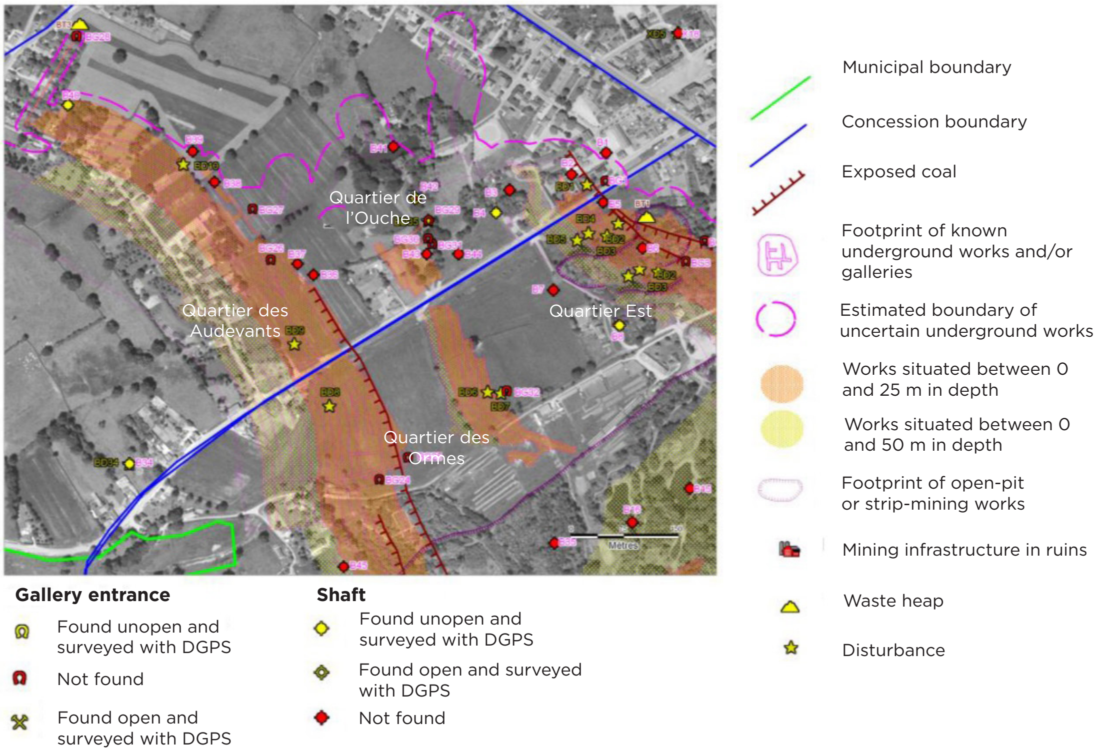

Figure 1: Example of an informative map

4.3 Mining hazard evaluation stage

4.3.1. Contents of the hazard evaluation report

The hazard evaluation report first presents the results of the information stage, described in Section 4.2, as well as the associated information maps.

The report then describes the hazard evaluation stage:

- first, it lists the hazards identified on the mining site. It may be the case that some phenomena that were initially predicted due to the configuration of old mining works and/or comparison to similar sites are ultimately not taken into consideration; in this case, it is important to explain the reasons;
- second, for each type of hazard considered, the potential phenomenon and the mechanisms contributing to it are examined. Next, the hazard's severity is evaluated by assessing and cross-referencing its intensity and predisposition as described in Chapter 2.2. Multiple typologies corresponding to distinctly different mechanisms may appear for a single hazard (for example, a localized collapse may occur due to the failure of a mine shaft, gallery or underground cavity). In this case, the hazard evaluation must address these specific issues so that no information is lost on the configuration or type of mine associated with the hazard.

Finally, the report presents the principles used to map the hazard, for each phenomenon and for each type or configuration within the phenomenon. This includes an explanation of the margins used, due to the surface repercussions and consequences of the potential event (margin of influence) and due to the uncertainty of the positioning of mining works and structures in relation to the surface (margin of uncertainty). Illustrative diagrams are appreciated because they aid in comprehension.

In the sections detailing the hazards, the principles for evaluating and mapping each phenomenon are presented.

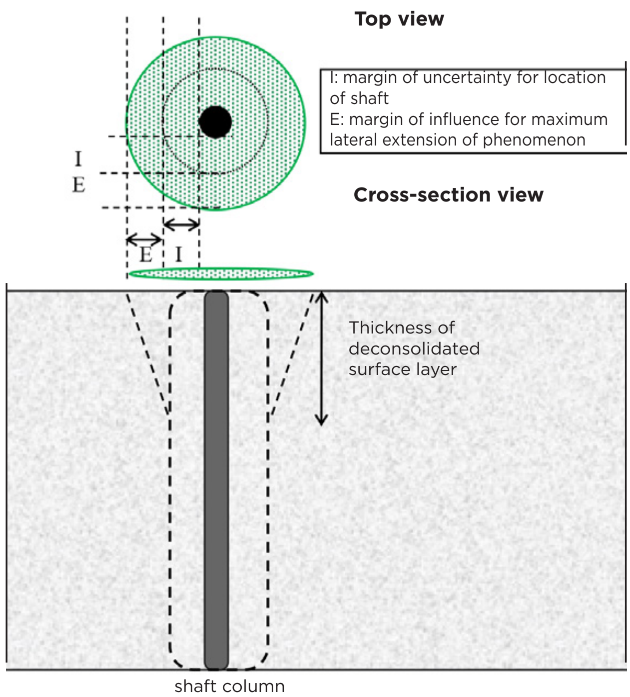

Figure 2: An example of a presentation of the margin for a "localized collapse" hazard linked to the presence of a shaft. The margin of influence E is added to the margin of uncertainty I

4.3.2. Hazard maps

Hazard maps are created for each potential phenomenon (phenomena may be grouped together if this does not alter the reading), for a given municipality or group of municipalities. These maps help visualize the area of the hazard and its severity (low, medium, high). The position of mining works (or the main ones among them) is often included to facilitate tracking.

These maps and the reports that go with them serve as a basis for public notifications to municipalities and for recording identified hazards in an urban planning document. They are not sufficient to be used alone: they must be accompanied by a hazard study report that explains the analysis process.

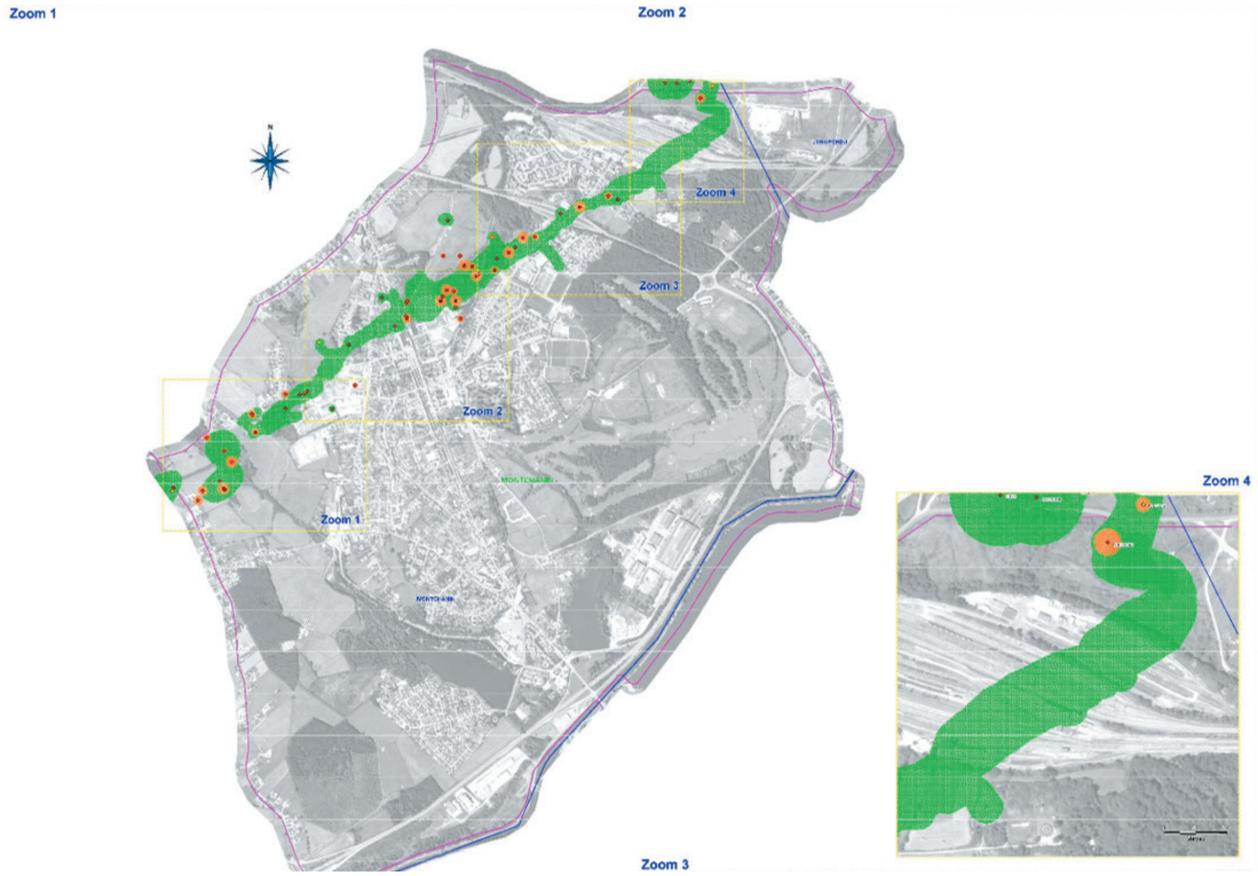

Figure 3: Example of hazard map and zoom insert on an orthophoto plan background. The localized collapse hazard linked to underground works is shown here in green, and the one linked to works connecting to the surface is represented by circular perimeters.

5 HAZARDS LINKED TO GROUND MOVEMENTS

5.1 Origin of potential phenomena

Mining operations consisted of extracting material, sometimes in large quantities, in order to be able to market a portion in the form of ore. The excavations created by mining, both underground and open-pit, irreversibly modified the rock masses where the ore was found. At the same time, mining was accompanied by the construction of structures for depositing waste and processing residue which are likely to undergo changes over time.

5.1.1. Underground mining works

The majority of mining in France was done in underground works. A highly diverse range of exploitation methods were used, depending on the nature of the deposit and the development of new techniques. From the perspective of post-mining residual ground movement risks, two main types of method can be distinguished: operations in which cavities were fully treated after extraction, and those that left large cavities remaining after the mine was shut down.

In mines where cavities were fully treated (intentional caving or pillar extraction), the collapse or refilling of cavities dates to the period of operation. Thus, all that remains after closure is a possible evolution of the land restored by caving (residual subsidence, settlement) as well as some empty spaces linked to infrastructure galleries that may give rise to localized collapses.

In so-called partial exploitations where there are still large residual empty spaces (rooms and pillars, empty rooms, dissolution cavities), the stability of old works may be affected by the alteration or aging of the material or by modifications in the environment of the underground structures. In particular, some materials such as salt are highly sensitive to water circulation. Due to the persistence of these large cavities, these mines may, on top of the phenomena associated with operations where cavities were fully treated, cause major subsidence or even generalized collapses. In both cases, the deeper the mine, the more its effects on the surface will be minimized.

The extent of potential areas of instability depends on the deposit's configuration. Exploitations with steep slopes are less likely to produce disruptions extending over large surface areas than flat exploitations of medium or shallow depth, since these are developed inside vast sedimentary basins.

These underground works are inevitably accompanied by structures (shafts, galleries, etc.) built to enable extraction, transportation of workers, ventilation or other functions necessary for or connected with mining activity. Many of these structures come into contact with the surface; these are called "structures connecting to the surface." They are not guaranteed to be stable if the closure is absent, insufficient or aged. Their instability generally causes localized collapses that may be widespread in certain cases of peculiar geology or if there is a presence or inflow of water. Thus, these structures are an integral part of a "ground movements" hazard study.

5.1.2. Open-pit mines

Depending on geological context, where the depth and content of the deposit and the geological context permitted, miners have been able to extract ore from open-pit mines. The oldest mines were made in this manner, when ore was found on the surface, and were generally small-scale operations until technological advances made more structured extraction possible.

During the course of a mine's lifespan, when technical or economic conditions proved advantageous, even larger open-pit mines could be created in order to extract most, if not all, of a deposit close to the surface. The process consisted of digging wide pits, sometimes after removing a thick layer of surface earth, from which the ore would be extracted. Some of these pits were expanded to vast dimensions (several hundred meters).

The choice of exploitation method, which mainly depended on the geometrical dimensions of the pit's sides, was made based on optimizing the balance between economic profitability (limiting the volume of overburden to be removed) and the stability of the mine's structure (avoiding overly steep sides, which could cause collapses).

Under the effects of time, water and ice erosion, these sides—which are generally formed of rock benches or faces, but also sometimes from surface soils in the case of shallower pits—often undergo instabilities that can range from simple rock falls or gullying to mass destabilization of a slope face. The combination of the geological nature of the exploited land, its fractures and the shape of the pit's slopes determines the volume of potentially unstable masses as well as the mechanism likely to cause a failure.

5.1.3. Waste structures

The exploitation of mines, both underground and open-pit, has often led to deposits of mining residue near extraction sites. A distinction is made between residue from exploitation and/or exploration and residue from the "process" of treating and beneficiating ore.

Exploitation residue, also called waste rock, is primarily composed of granular material deposited using a dry method. It can be direct waste (from drilling shafts or tracing galleries in rock, for example) or mineral waste (usable material content is lower than what is economically exploitable at the time of deposit).

Once amassed, this residue forms piles of material commonly referred to as tailings, waste dumps or slag heaps, depending on the shape of the deposit and regional terminology.

Processing residue is composed of a mixture of fine solid materials and water collected at the end of the processing chain, when all operations for the beneficiation of the ore have been completed. It frequently contains a high content of companion minerals or secondary substances such as iron sulfides and their oxidation products. It can also contain significant residual concentrations of reagents used in the extraction, separation and concentration of valuable metals. It may also contain combustible materials.

These residues were decanted in retention basins placed in sectors whose topography and geology were suited to this purpose (sides of valleys, thalwegs, etc.) or contained using retention structures built near the storage area. These structures, commonly and often improperly called *dykes*[3], may actually be *dams*, and are often constructed using waste rock from the mine; their main purpose is to contain and store the residue from processing ore.

The nature and granulometry of the materials used to build these structures can vary greatly. The rupture or deterioration of waste deposit structures generally results from unfavorable changes to one or more factors governing the intrinsic mechanical behavior of the material or residue, most often the surface on which they are located. The types of disturbances most likely to affect these structures are, in ascending order of intensity: superficial movements (gullying, superficial landslides), large-volume landslides and mudslides.

5.1.4. Summary of possible disturbances for each type of former mining structure

Table 2 below provides a summary of the principal "ground movement" disturbances traditionally encountered based on two traditional input factors (types of phenomena and types of mining structures).

It can be used to determine, for each type of mining structure, the main instability phenomena that are likely to affect the surface terrain located within its area of influence. And vice versa: the table can be used to list all structures that are likely to initiate a given type of disturbance that has been mapped.

3 - The terms "dyke" and "dam" also have legal definitions and thus should be used with care in hazard studies.

Table 2: Summary of principal potential disturbances by type of former mining structure

Mining structure	"Ground movement" phenomena							
	Localized collapse	Continuous subsidence	Discontinuous subsidence	Crevices	Generalized collapse	Settlement	Slope movements (loose surface ground)	Rock slope movements
Underground structures								
Deep total extraction		Possible		Possible in specific cases (see 5.5)		Possible		
Partial extraction	Possible	Possible	Possible in specific cases (see 5.4)	Possible in specific cases (see 5.5)	Possible in specific cases (see 5.6)	Possible		
Vein deposit mining	Possible	Possible				Possible		
Salt mining via dissolution cavities	Possible	Possible			Possible in specific cases (see 5.6)			
Old mines in combustion	Possible	Possible				Possible		
Mining structures connecting to the surface	Possible	Possible				Possible		
Outcropping areas	Possible					Possible		
Open-pit mines								
Backfilled open pits	Possible					Possible		
Unbackfilled open pits in hard rock								Possible
Unbackfilled open pits in soft rock							Possible	
Waste structures								
Tailings, slag heaps, waste deposits, "dykes"	Possible					Possible	Possible	Possible
Settling pond, retention of fine materials with or without dyke						Possible	Possible	

5.2 Localized collapses

5.2.1. Description, mechanisms, effects

Localized collapses are characterized by the sudden appearance on the surface of a collapse crater, which generally varies from a few meters to several tens of meters in diameter. The depth of the crater depends mainly on the depth and dimensions of the mining cavities that caused it. While in the majority of cases, the crater is only a few meters deep, in some specific configurations it can reach or even exceed ten meters (collapse of a mine shaft, for example).

Depending on the mechanism that initiated the disturbance and the nature of the subsurface terrain, the walls of the crater may be subvertical or sloped, giving it a characteristic funnel shape.

The scale of these disturbances and the suddenness of their appearance on the surface make localized collapses potentially dangerous to people and goods, especially when they occur in or near populated areas.

Photograph 1: Example of a localized collapse

The principal mechanisms or scenarios that cause localized collapses are briefly presented in Table 3 (p.21).

5.2.2. Localized collapse: hazard qualification

5.2.2.1. Qualification of intensity

The phenomenon of localized collapse is likely to cause damage to the safety of people and property present on the surface.

The **diameter of the collapse** is the main influencing factor on the foreseeable consequences for the safety of the people and property present in the area of influence. Thus, it is this parameter that is used as the representative value. Logically, the maximum diameter will be the one used in the evaluation (stabilized funnel-shaped configuration). However, keep in mind that in terms of dangerousness, it is actually the immediate diameter (area affected at the time of the collapse), which is sometimes significantly smaller than the previous one, that counts.

The crater's depth can also influence the dangerousness of the phenomenon, but it often proves difficult to predict, especially when it comes to sinkholes and shaft backfill collapses.

The principal factors that are likely to influence the value of the collapse diameter include: the dimensions of residual voids in underground mines (volume of galleries), as well as the thickness and type of the overburden soil. Regarding this point, note that the thickness and type of the subsurface soil play a dominating role, because its collapse (when the soil is loose) may contribute greatly to the dimensions of the collapse funnel on the surface.

Table 4: Localized collapse: intensity classes

Intensity class	Diameter of collapse
Very low	Self-backfilled collapses in immediate proximity to the surface (centimeters in depth)
Low	Ø <5 m
Moderate	5 m <Ø < 10 m
High	Ø > 10 m

In France, hazard maps created for "ground movements" linked to the presence of old mines show that the phenomenon predicted to be largest in terms of hazard surface area is the localized collapse. This led to a statistical analysis conducted on more than 1800 localized mine collapses [5]. This analysis shows that:

- 90% of mining collapses are less than 10 m in diameter: collapses of very large diameters are exceptional and correspond to very specific mining contexts that clearly do not fall in the category of "common cases";
- more than a third of collapses are strictly less than 3 m in diameter and nearly two thirds are less than 5 m in diameter;
- in low hazard zones, more than half of recorded collapses are less than 3 m in diameter and over 80% are less than 5 m in diameter;

Furthermore, the CSTB (French Scientific and Technical Center for Building) provides construction provisions for areas likely to be affected by a localized collapse of less than 5 m in diameter ([13]).

5.2.2.2. Qualification of predisposition

Evaluation of a site's predisposition to a localized collapse depends on three categories of parameters:

- the presence of similar phenomena on the site or in similar or identical configurations (geology, mining conditions, etc.);
- parameters linked to the underground structure's predisposition to failure: these mainly include the width of the gallery or room and the characteristics of the primary roof beds (thickness, resistance, fracturing);

- parameters linked to predisposition to instability rising to the surface: here, the nature and thickness of the overburden layers will determine the bulking factor or the formation of a stable vault.

In addition to these parameters, there is a number of other aggravating or triggering factors such as the hygrometry and alteration of surrounding materials, creeping and weathering, hydraulic overloading, seismic activity and anthropogenic factors (human activities on the surface).

The table 5 identifies the classes of predisposition to localized collapse of underground mines.

Table 3: Localized collapses: principal initiating mechanisms

Initiating mechanism	Propagation mechanisms	Key comments, *estimated frequency of configurations* (in France)
Localized collapse due to rupture of a gallery roof: the sinkhole phenomenon	A collapse is called a **sinkhole** when the instability affecting the surface results from a chimney's gradual rising to the surface followed by a collapse that starts inside an underground excavation (gallery, mining room, etc.).	The appearance of this type of disturbance on the surface only occurs with shallow-depth structures, whether they are isolated galleries or larger mined areas (cuts, rooms and pillars, etc.). Experiments conducted on several mining areas showed that, absent unusual geological or mining factors, when old mining cavities are deeper than fifty meters (and sometimes less), they are no longer likely to cause this phenomenon on the surface. ***Very frequent***
Collapse by failure of isolated pillar(s)	In a partial mine exploited using the rooms and pillars method and then abandoned, when one (or more) pillar(s) deteriorates, a collapse can appear on the surface when the mine is not deep enough, and the overburden is not sufficiently thick or rigid. These are called **isolated pillar failures.**	The appearance of this type of disturbance on the surface only occurs with shallow-depth mines (around 50 m) exploited with rooms and pillars and in specific conditions. ***Infrequent*** given the specific conditions required.
Mine shaft collapse	In old mine shafts that have been improperly backfilled (using materials that may remobilize, particularly in the presence of water), the backfill may **run out**; that is, it may sink into connected underground workings, resulting in the formation of a crater on the surface with the same dimensions as the shaft column. This backfill run-out may be accompanied or followed by the collapse of the shaft lining and of any surrounding loose ground, which is generally present near the surface. This causes a collapse funnel to form, the size of which depends on the geological, hydrogeological and mechanical characteristics of the surrounding land. The shaft lining may collapse when a shaft is not backfilled and is improperly plugged.	Backfill run-out: ***frequent*** in very old shafts, especially during the mine water uprising phase. Mine shaft collapse: depends on the nature of the lining, presence of safety structures: ***Infrequent***
Vein head failure	Mining a vein close to the surface may lead to the collapse of the top of the vein. This failure may develop through shearing along the interfaces between the vein and the walls (this is called a crown pillar collapse) or by subvertical shearing of the wall.	The formation of a crater on the surface depends strictly on the characteristics of the mine and the surrounding land, but may differ from a sinkhole in its more elongated shape, which forms along the line of the vein. While these collapses very rarely exceed ten meters in breadth, their length can reach several tens of meters along the line of the vein. ***Moderately frequent***
Collapse of a backfilled sloped worksite	This mechanism, which is most likely to affect steeply sloped layers (veins, steeply inclined seams), is quite similar to that of a shaft backfill collapse. When a mine is exploited up to the surface and then its voids are backfilled, the collapse of an underground retaining barrier may cause the backfill materials to slip into the deepest voids. This slippage may cause a collapse on the surface, the shape and dimensions of which depend directly on the conditions of the mine.	***Infrequent***
Combustion	In certain very specific configurations, the combustion of carbonaceous materials present in underground works or in solid combustible waste deposits from old mines may lead to the formation of small cavities near the surface which may collapse. In this scenario, potential consequences to victims are exacerbated due to the temperature of the smoldering earth and the vapors and gases emitted.	***Infrequent***
Dissolution	The mechanism of dissolution may lead to the formation of localized collapses in deposits or shallow underground voids from evaporite mining (salt, potash).	***Infrequent***

Table 5: Localized collapse: characterization of predisposition

Predisposition of an area to a localized collapse	Characteristic features
Very likely	• the phenomena has already occurred several times in the area; • **and** conditions are right for the phenomena to occur multiple times in the area at the scale of a human life (confidence on mines exitence, sufficient knowledge of characteristics to show that the phenomenon is likely to occur, petrography known to be favorable to the development of the phenomenon); • **or** the area is known to have deteriorated in condition in comparison to a previously established "sensitive" predisposition; • **or** the area is known to present aggravating factors that may favor the occurrence of the phenomenon.
Likely	• a similar phenomenon has already occurred in the area or the phenomenon has already occurred in a site similar to the area concerned; • **and** the conditions for the phenomenon occurring in the area are not met with as much certainty as in "very likely" cases (for example: presence of a mine is known, but there is a lack of knowledge on its dimensions, the state of its backfill, its petrography).
Unlikely	• the phenomenon is unlikely to occur in the concerned area, but experience feedback is insufficient to discount it entirely (known presence of mining works but no similar incident recorded); • **and** there are no known aggravating factors likely to contribute to the phenomenon's occurrence.
Very unlikely	• petrography is particularly favorable to stop a sinkhole from forming (thick, solid, resistant layers) • **or** the presence of mining works is suspected or uncertain (area is close to outcroppings whose geological characteristics are favorable to mining, for example; deductions based on available information, etc.); • **or** the presence of mining works is known, but their localization is uncertain (the surface area of the works is low compared to the area of uncertainty); • and the phenomenon is unlikely to occur in the concerned area but experience feedback is insufficient to discount it entirely;

A shaft's predisposition to collapse must take into account two possible mechanisms: the run-out of the backfill inside it, and the failure of the top of the shaft.

Shaft backfill run-out is sensitive to predictable hydrogeological variations in the structure (rising water, water table fluctuations), the presence of galleries connecting to the shaft and not plugged with dams, the age of the backfill and the presence of aggravating factors in the shaft's environment, such as vibrations or overloading. In general, the potential heterogeneity of the backfill and the number of connections to the shaft increases with the shaft's depth. In the absence of more precise information on the shaft, especially for very old ones, this depth criterion is often factored into the evaluation of predisposition.

The predisposition to the *collapse of the structure built on top of the empty shaft* (e.g., wooden cap, brick vault, slab, plug). In this case, the structure's characteristics (resistance, dimensions), its long-term alterability, the nature of the shaft's lining or covering and the nature and resistance of surrounding ground directly influence its predisposition to failure.

These two phenomena may occur at the same time. Though such cases are relatively rare, they should not be discounted. Thus, the unfavorable factors that must be taken into consideration are the age and degradation of the shaft lining as well as the presence and thickness of loose sub-surface ground that may cause this phenomenon to extend beyond the diameter of the shaft itself.

5.2.3. Localized collapse: hazard map

The hazard map includes:

- a margin of influence corresponding to the potential site coverage of the collapse crater;
- to which a margin of uncertainty is added.

The collapse crater's coverage; that is, the foreseeable diameter of a sinkhole on the surface is the result of an analysis based on:

- experience feedback available on the site concerned (characteristics of observed sinkholes);
- knowledge of the geometry of the underground void;
- the nature and thickness of loose surface ground in which the crater may have a variable slope depending on the type of material.

5.3 Continuous subsidence

5.3.1. Description, mechanisms, effects

Subsidence is characterized by a readjustment of surface ground induced by the collapse of underground cavities due to the extraction or disappearance (via dissolution, combustion) of mineral deposits. Subsidence is generally slow, progressive and flexible, and takes the form of a topographical depression with no major breaks, giving it a bowl-shaped appearance (Figure 4). This type of disturbance also occurs with flat deposit mines that are very deep (several hundred meters) and of large horizontal extension, where exploitation of seams has left large residual voids after extraction.

The amplitude of subsidence is directly proportional to the opening of the underground works. The proportionality coefficient depends on the depth of the mining works and the nature of the methods used to exploit and treat the voids (e.g., caving, backfilling). In most cases, the maximum amplitudes observed at the center of the depression, during or after operations, are on a decimetric to metric scale.

Generally, it is not so much vertical displacements which principally affect surface buildings and infrastructures, but ground deformation (e.g., differential horizontal displacement, flexion, slope development). Depending on its position in the subsidence depression, differential horizontal displacement may take the form of shortening (compressed zone toward the inside of the depression) or extension (tensile zones towards the outside of the depression).

Deformations and slopes are proportional to the maximum subsidence in the center of the depression and inversely proportional to the depth of the mining operation. Thus, for a single thickness exploited, the deeper the exploitation, the less severe the effects.

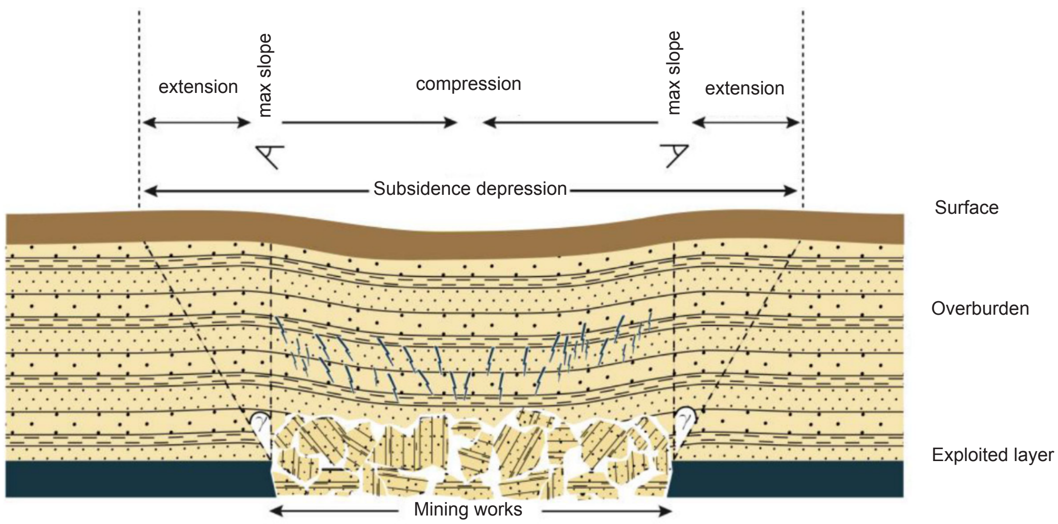

Figure 4: Principles of a subsidence depression and its effects on the surface.

Like most other instability phenomena, mining subsidence is not strictly limited to the contours of underground works. The angle between the vertical and the straight line joining the underground perimeter of the workings and the outer limit of the surface subsidence depression is called the "angle of influence" (Figure 4). Depending on the nature and thickness of the overburden, the angle of influence usually varies between ten and forty degrees. The existence of a dip in the mining works also has a direct influence on the angle of influence, as does the presence of major geological accidents (faults).

The principal mechanisms or scenarios that cause subsidence are briefly presented in the table below.

Table 6: Continuous subsidence: principal initiating mechanisms

Initiating mechanism	Propagation mechanisms	Key commeants, *estimated frequency of configurations* (in France)
Underground collapse provoked in "total" extraction operations, in stratified land formations	Collapse of the roof layers of the underground mining operation, swelling of collapsed materials, sinking of overburden, gradual appearance of a depression on the surface.	Almost all subsidence occurs during extraction; the period of residual subsidence is limited to a few years. Recurring subsidence may occur due to variations in environmental conditions ***Very infrequent*** due to the old age of the mining works.
Underground collapse in partial extraction operations in stratified formations	Deferred failure of one or more stabilizing elements of large underground mining works (e.g., pillars, middling, roof, wall). Mechanisms of propagation toward the surface similar to previous case	The phenomenon may be initiated several years or decades after the mine has closed down. ***Moderately frequent*** but specific configurations (large underground mining works)
Underground collapse in vein mining operations	Several possible mechanisms depending on method of operation	Occurs when the vein is exploited over a wide extension, is very thick and not too deep. The deposit's angle of dip also influences the likelihood of this effect (little to no likelihood if the deposit is very steeply dipped) [22]. ***Infrequent***
Underground collapse of salt dissolution cavities Salt brine on top of the salt layer created or modified by an old mining operation (using pumping and/or dissolution method)	Dissolution of salt on top of the salt layer by unchecked inflow of freshwater that continues after the mine has been shut down. Several possible mechanisms depending on method of operation.	Depending on configuration, dissolution may: • be relatively concentrated to small areas and generate small but evident subsidence depressions; • or develop over a wider area in the periphery of collapsed areas or even across the entire layer of brine. ***Moderately frequent***

5.3.2. Continuous subsidence: hazard qualification

5.3.2.1. Qualification of intensity

Intensity is qualified by the horizontal differential deformations and the effects of **slope development**, which are generally most damaging to property located on the surface. Because these two parameters are directly related, slope development is the primary factor used to qualify intensity. Intensity classes qualify the predicted effects on property, even though when certain deformation values are exceeded, the disturbances inflicted on buildings may endanger the safety of people.

The threshold values presented in the table below are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 7: Continuous subsidence: intensity classes

Principal evaluation factors	Intensity class	Slope (%)
Opening of underground mining operations, method of operation, rate of extraction, depth and breadth of panel extraction, nature of overburden, slope of overlying layers, surface topography, presence of geological accidents, etc.	Very low	P <1
	Low	1 <P < 3
	Moderate	3 <P < 6
	High	P > 6

5.3.2.2. Qualification of predisposition

Regardless of the mining context, when indications of past "continuous subsidence" movements (still visible on the surface or described in the archives) are present in a nearby sector with similar geological and mining characteristics, this can contribute to increasing predisposition to the development of these types of events in the future.

Other criteria for increased or decreased predisposition are described below:

Table 8: Continuous subsidence: predisposition criteria

Mining context	Main criteria for relevant/increased predisposition	Main criteria for non-relevant/decreased predisposition	Comments
Total extractions by roof caving	Period of several years between the date of underground mining operations and the hazard study (very rare scenario).	Period between mining and hazard study longer than ten years General scenario	Future movements are possible (presence of water/anthropogenic overloading). In this case, refer to "settlement" hazard
Partial extraction operations in stratified formations	**Linked to stresses on roof-supporting structures and pillars in mines:** - High extraction rate - Deeper extraction - High width/depth ratio of extraction - Operational conditions of adjacent sectors, which may increase stresses - Geometric characteristics and positioning of pillars **Linked to resistance of mine pillars and roof** - Geomechanical characteristics of the rock - Predisposition of the rock to alteration/aging - Inflow of water or variation of water level - Faults, fracturing in the rock	Low extraction rate Low or insufficient width/depth ratio of extraction Mine not deep enough for stresses on the mine workings to be the most relevant criteria	As the mine's depth increases, predisposition also increases but intensity decreases
Salt mines operated by dissolution or dry mining	Presence or inflow of unsaturated water with strong dissolution potential in or near cavities. Structures that connect to the surface, are failing or improperly plugged, facilitating the flow of water Water permeability of surrounding ground affected by nearby mining operations *Dip of the top of the salt layers, which can lead to a propagation effect called "up-dip," geological structures or accidents facilitating the infiltration of unsaturated water with dissolution potential*	Cavities separated from water by geological formation forming a natural seal. Water is salt-saturated with low dissolution potential Mine has been properly plugged for long term *Absence of dipping, unfavorable geological structures or accidents*	This phenomenon may be permanent or may diminish then disappear with a return to a favorable hydrogeological balance
Vein deposit mines	Deep extraction operations. Mining works are sloped or dipping but not subvertical. Backfilling is uncertain or absent	Mining works are steeply dipped or subvertical, backfilled Weak overlying layers.	Stress/resistance ratio criteria similar in principle to stratified formation mines

5.3.3. Continuous subsidence: hazard mapping

The hazard map of a subsidence must account for its margin of influence, qualifying the surface area that may be affected by a disturbance. This margin is often constructed based on the qualification of an *angle of influence.* This is done by using experience feedback from measurements taken during periods of operation and monitoring of surface disturbances. The angle of influence is defined by the expert based on:

- the mining context (see configurations above);
- the mining operational conditions in the area surrounding the underground area of the hazard;
- the geological characteristics of the overburden.

5.4 Discontinuous subsidence

5.4.1. description, mechanisms, effects

Discontinuous subsidence is a phenomenon that requires specific mining conditions and overburden characteristics [4]. It may occur when the following conditions are met:

- it requires the existence of partial-extraction mining works (particularly those using the rooms and pillars method) situated at several hundred meters in depth;
- it requires the existence of large residual cavities in these mining works (no backfilling or internal collapses);
- the overburden of the mining works is mainly composed of brittle materials.

In this scenario, the roof cracks by shearing along its supports (edges of the panel). The crack can then spread to the surface, causing a mass collapse of the overburden. The area of subsidence on the surface is then outlined by a network of cracks along the periphery of the panel in question.

The possible development of these cracks along the edges of the depression is what distinguishes discontinuous subsidence from continuous subsidence. These cracks may present structural risks for buildings situated in their area.

Another characteristic of discontinuous subsidence is the kinetics of the event, which may be much more rapid than in the case of continuous subsidence. While the phenomenon generally originates below the surface over a period of several days (fracturing and crushing of pillars, preliminary fracturing of roof), it can often manifest suddenly on the surface (collapse of a fragile roof) and be accompanied by one or more seismic tremors that can weaken buildings that are less adapted to this type of stress.

5.4.2. Discontinuous subsidence: hazard qualification

5.4.2.3. Qualification of intensity

Given the dangerousness and suddenness of discontinuous subsidence when it appears on the surface, it is automatically assigned a moderate to high level of intensity.

5.4.2.4. Qualification of predisposition

Discontinuous subsidence requires very specific conditions to occur, as described in 5.4.1.

Evaluating predisposition to discontinuous subsidence requires an expert assessment in order to establish the possibility of the convergence of these conditions.

5.4.3. Discontinuous subsidence: hazard mapping

As is the case with continuous subsidence, the hazard map must account for the margin of influence of a discontinuous subsidence, qualifying the surface area that may be affected by a disturbance.

In the case of discontinuous subsidence, the physics of the phenomenon and experience feedback on events of this type show that the collapse is generally subvertical along the edges of the area that collapsed beneath the surface. Given the major role that some faults can play in the propagation of this type of instability, an angle of influence of 10° is used to define the margin of influence.

5.5 Crevices

5.5.1. Description, mechanisms, effects

From a purely geometric standpoint, crevices are defined as visible discontinuities with openings ranging from centimeters to decimeters in width, length extending from several meters to several tens of meters, and variable depth of up to several meters.

Multiple different types of phenomena described in this handbook may be the cause of their formation: subsidence, discontinuous subsidence and generalized collapses.

Nonetheless, we are devoting a section to crevices because in certain specific conditions, their appearance and discovery on the surface can occur several years, even tens of years after they are formed (Figure 5).

Crevices caused by the effects of extraction are often discovered during anthropogenic works on the surface (leveling for roadwork, infrastructures or buildings). More rarely, they may appear on the surface during certain kinds of weather events (heavy rainfall, freeze/thaw cycles) or during anthropogenic activities that generate heavy water flow (pipeline leaks). In these two scenarios, the predominant initiating mechanism is when water flow mobilizes fine materials on top of or inside the crevice, which then sink to the bottom, bringing with them any surrounding loose earth. The phenomenon is generally sudden, even near-instantaneous.

There are two sectors in France where most, if not all, of crevice disorders are found, in these particular conditions of delayed appearance on the surface, long after mining operations have ended. These sectors are the Lorraine coal basin and the Lorraine iron basin.

Though these two mining areas are very different, they share two criteria that are favorable to the *formation* of crevices, which may be extrapolated to other mining configurations if needed: first, the existence of collapsed sections that have led to overburden subsidence; and second, the rigid and brittle geomechanical characteristics of the overburden.

When subsidence occurs, the overburden undergoes vertical and horizontal shifts. Overburden that is constituted of rigid, brittle rock with no major initial discontinuities tends to fracture and can thus generate surface crevices later on.

The main criterion for delayed *appearance* on the surface is the presence of loose surface earth that may be remobilized by erosion, specific or unusual weather events, or even anthropogenic activities.

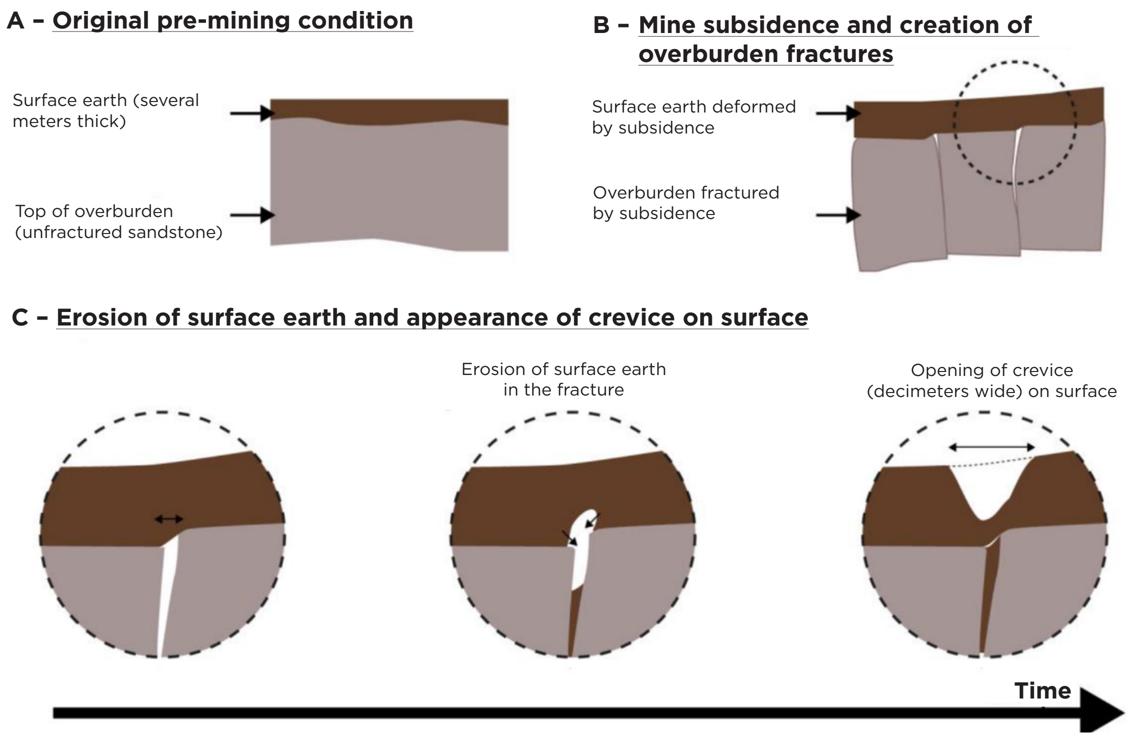

Figure 5: Illustration of mechanisms causing crevices in overburden and their appearance on the surface after changes in surface terrain (according to J.P. PIGUET and O. DECK, 2014)

5.5.2. Crevices: hazard qualification

5.5.2.1. Qualification of intensity

Although these disturbances are characterized by high anisotropy (long length), which may be an aggravating factor if building foundations or infrastructures are built on top of and along the length of the crevice, the **extension – or width** – of these crevices is the primary factor in determining the phenomenon's intensity on the surface (including the margin of influence).

The actual depth of a crevice is difficult to evaluate since this type of discontinuity is filled with loose materials which may conceal the bottom. Thus, depth is not a factor used to evaluate intensity.

Experience feedback on crevices observed in France indicates an average width on a scale of approximately 20 cm (Lorraine coal basin) to 50 cm (Lorraine iron basin; this value is tempered by a much lower number of observed cases [26]). In specific conditions of sloped terrain on a hillside, the width may be larger due to the erosion on the edges in the slope, which enlarges the discontinuity. However, the crevice generally does not exceed one meter in width. The most unfavorable case identified in France was an inflow of water that caused a sudden evacuation of materials, creating a gully on the surface; the resulting crevice had a width of 2 meters.

Experience feedback on these disruptions in the affected basins shows that they have only led to the appearance of cracks on buildings without affecting their integrity. However, crevices can cause failures in underground pipelines and water supply networks.

In these conditions described for the appearance of a crevice long after mining operations have ended, the mine movement that caused a slope to develop on the surface occurred, then stabilized. Then there is a sudden migration of loose material between the edges of the crevice. Also, there is generally no significant differential vertical displacement from one edge to the other.

These considerations are used to evaluate intensity as shown in Table 9. The threshold values presented in the table below are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 9: Crevices: intensity classes

Intensity class	Width of crevice on surface
Very low	w < 0.5 m
Low	0.5 m < w < 5 m

5.5.2.2. Qualification of predisposition

Predisposition to the crevice phenomenon is primarily linked to the presence of collapsed sections of underground mines that have led to overburden subsidence; the rigid, brittle nature of the overburden rock; and the presence of loose surface earth causing the delay of its appearance on the surface.

A recent study conducted by GEODERIS in the Lorraine coal basin [3] indicates that the value of the maximum deformation of the subsidence depression or depressions, located on top of collapsed underground mine sections that are flat or slightly dipped, can be considered a major parameter for evaluating predisposition. The higher this value, the greater the slope development and tensile stresses in the overburden, thus causing the appearance of fractures in rigid, brittle ground.

Predisposition to crevices on top of steeply inclined mining areas, a context in which numerous crevices were observed in the coal basin, depends on the height and density of the mining works.

The table 10 lists aggravating and limiting or excluding factors for this predisposition.

Table 10: Crevices: aggravating factors, limiting or excluding factors for predisposition

Aggravating factors	The *mining method* of caving has a more aggravating influence on crevice predisposition than the rooms and pillars method. The presence and orientation of *major geological faults or discontinuities* has facilitated fractures and the spreading of crevices toward the surface.
Limiting or excluding factors	The presence of *loose formations of sufficient thickness* on top of a rigid overburden prevents the fractures from reaching the surface and generating crevices. Subsidence on top of collapsed mining areas of *small extension* lead to surface deformation values that are negligible to zero. The *position of a section of surface in relation to the underground collapse* is an important criterion: the center of a correctly outlined subsidence depression is an area where land deformation occurs solely by compression. Consequently, the formation of fractures and the appearance of crevices is not possible. When a single section of surface has been affected by multiple subsidence events (successive or delayed mining of panels located at different depths), the process of outlining compressed or tensile areas is much more delicate and requires special expertise. However, this can constitute a limiting or even excluding factor when an area that was initially affected by tensile movements is later subject to compression movements: the fractures initially generated then close back up.

5.5.3. Crevices: hazard mapping

When a single mine panel has collapsed, the position of potential crevices is within the deformation extension area of the subsidence, which is shown in yellow in Figure 6. When multiple subsidence depressions are superimposed, mapping is more complex and requires appropriate expertise.

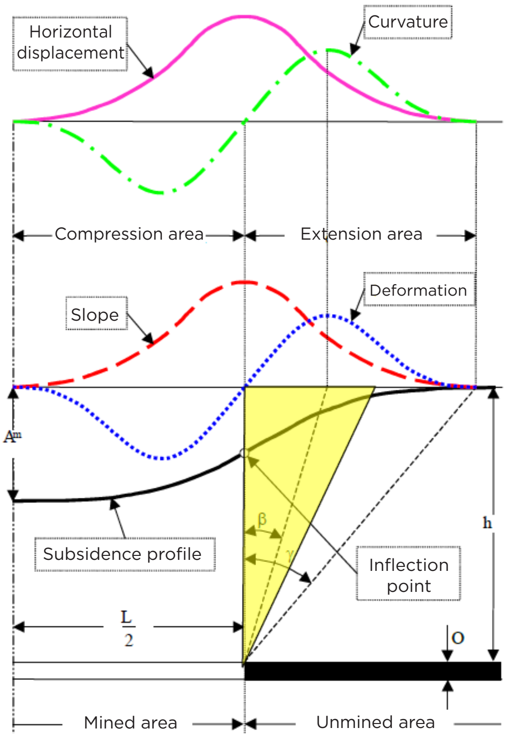

Figure 6: Profiles of deformation and slope development in a subsidence depression for a single mined coal panel.

The yellow area is the area of potential crevices (with O = coal layer opening; h = depth of the mined layer; A_m = maximum amplitude of subsidence produced on surface; L = width of the mined area; β = angle of maximum deformation, γ = angle of influence).

5.6 Generalized collapses

5.6.1. Description, mechanisms, effects

Generalized collapses, also known as mass collapses, manifest themselves by an often dynamic collapse (lasting several seconds) of all or part of a mining operation, thus affecting the stability of surface land over areas that can extend up to several hectares. The part of the collapse affecting the central area may reach several meters in height, or even several tens of meters in the case of collapses of salt dissolution cavities. This central area is surrounded by a border of open, subvertical fractures that mark out "stairs," which can cause severe damage to people and property on the surface.

Though rare, these phenomena can have potentially serious consequences because they release a considerable amount of energy. They may be accompanied by seismic tremors and blast effects, which are likely to project materials over long distances through open galleries and shafts.

The principal mechanisms or scenarios that cause generalized collapses are briefly presented in the table below:

Table 11: Generalized collapse: principal initiating mechanisms

Initiating mechanism	Sensitive configurations Propagation mechanisms	Key comments, estimated frequency of configurations (in France)
Sudden collapse of abandoned pillars resulting in roof failure	*Underground mining area with a high extraction rate, large-volume voids, undersized pillars or multilevel operations.* Overburden composed of one (or more) rigid layer(s) which reach their limit of elasticity and suddenly fail. Sudden overload on pillars, which fail simultaneously. Sudden collapse of the overburden (in several seconds)	The phenomenon may be initiated several years or decades after the mine has closed down. The configurations required for this phenomenon make it. ***Very infrequent***
Domino effect pillar failure	*Pillars in an underground structure that have reached the limit of stability, affected by the modification or development of a triggering factor.* Progressive failure of neighboring pillars. The overburden collapses, following the front of the underground cave-in. Less abrupt than the previous phenomenon (a few minutes to a few hours) but still potentially dangerous	The phenomenon may be initiated several years or decades after the mine has closed down. The configurations required for this phenomenon make it. ***Infrequent***
Collapse of saline dissolution cavities	Delayed roof failure of saline cavities. This failure may be due to additional dissolution, which enlarges the size of cavities until they reach the limit of stability of the structure. Significant increase of the hydraulic load inside the cavity can also lead to roof failure. Generally sudden failure of the cavity roof, with the movement kinetics depending on the evacuation of brine and the presence of a void in the cavity.	The phenomenon may be initiated several years or decades after the mine has closed down. The configurations required for this phenomenon make it. ***Very infrequent***

5.6.2. Generalized collapse: hazard qualification

5.6.2.1. Qualification of intensity

A generalized collapse is a movement with a large spatial extension whose occurrence, regardless of the amplitude of the surface drop (directly related to the opening of the works and the mine's extraction rate), may endanger the safety of people and property located within the area of instability.

Thus, there is no reason to define a reference magnitude to characterize the intensity of this type of disturbance, since the intensity class is always high—which is also due to a lack of protective measures that can help prevent the predicted consequences of such an event on the surface.

Table 12: Generalized collapse: intensity class

Intensity class	Description
High	Mass collapse of the surface

5.6.2.2. Qualification of predisposition

Regardless of the mining context, when indications of past "generalized collapse" movements (still visible on the surface or described in the archives) are present in a nearby sector with similar geological and mining characteristics, this can contribute to increasing predisposition to the development of these types of events in the future.

The predisposition of old, abandoned rooms-and-pillars mines to the development of a generalized collapse depends on the combination of two predispositions: failure of the underground structure and overburden failure.

Photograph 2: Effects of a generalized collapse on the surface

Table 13: Generalized collapse: predisposition criteria

Mining context	Main criteria for relevant/increased predisposition	Main criteria for non-relevant/decreased predisposition
Partial extraction operations in stratified formations	**Linked to underground conditions** • high stress in the pillars (related to the extraction rate, the depth of the works and the mining conditions of nearby sectors); • mine configuration favorable to failure (e.g., pillars too small, fragile materials, pillars poorly superposed); • presence of a large number of undersized pillars; • absence of "barrier pillars" that may block a collapse front from spreading; • other factors such as materials' sensitivity to water, wall behavior (e.g., risk of perforation, presence of cracks); • for salt mines operated using rooms and pillars, presence of aquifers or any large, open body of water (canals, rivers, lakes, etc.) likely to flow into the old mines and damage the pillars (by possible dissolution of pillars and/or weakening the walls of the mine). **Linked to the possibility of a sudden overburden collapse** • lateral extension of mine is sufficiently large in comparison to the thickness of the overburden; • presence of one (or more) stiff layer(s) in the overburden that may abruptly fail	Low extraction rate Low or insufficient width/ depth ratio of extraction Pillars correctly sized or oversized Mine not deep enough for stresses on the mine workings to be the most relevant criteria Absence of stiff layer(s) in the overburden, favoring a "subsidence" type phenomenon
Salt cavities	Cavity has large horizontal dimensions and shallow depth. Salt layer on the roof of the cavity is thin or even nonexistent. The fact that a cavity has already begun to develop within the ground covering the salt formation constitutes a factor highly unfavorable to the site's stability. Presence of a stiff layer in the overburden which enables, through stress resistance, the development of cavities with large extensions and leads to a sudden collapse of the surface. Existence of possible unsaturated water circulation contributing to salt dissolution and thereby increasing the size of cavities. Uncertainty on the exact dimensions of the cavity (very old mines with little available data, interconnected cavities).	Cavity has small horizontal dimensions Layer of salt on the roof sufficiently thick, contributing to structural stability Absence of stiff overburden, favoring a "subsidence" type phenomenon Cavities separated from water by a watertight geological formation, Water is salt-saturated with low dissolution potential.

5.6.3. Generalized collapse: hazard mapping

The hazard map of a generalized collapse must account for its margin of influence, qualifying the surface area that may be affected by a disturbance. This margin of influence is generally more limited than that of subsidence. In configurations favoring sudden failure of a stiff layer in the roof or overburden of an underground space or a salt cavity, the area of the collapse on the surface may come close to the area of the potentially unstable underground voids. However, due to the event's high expected intensity, the uncertainty of the position of the mining works, and the presence of loose materials on the surface that may increase the area of collapse, even after the event (when these materials reach an "equilibrium"), a safety margin is generally included.

5.7 Settlement

5.7.1. Description, mechanisms, effects

The term "settlement" in this context includes separate phenomena related to the rearrangement of surface terrain due to the presence of underground mining works, waste deposit structures, backfilled pits or mining structures, or due to hydrogeological disturbances linked to former mining activity.

The potential consequences are limited and without danger to human life. They mainly result from the fact that surface ground may be affected by differential settlements, which are likely to have negative effects on buildings and infrastructures.

The principal mechanisms or scenarios that cause generalized collapses are briefly presented in the table below:

Table 14: Settlement: principal initiating mechanisms

Mechanism	Sensitive configurations	Key comments, estimated frequency of configurations (in France)
Rearrangement of land on top of collapsed, improperly stoped or improperly backfilled former mining areas	Land overlying underground mines exploited using a roof caving method (cut-and-fill or pillar extraction mining) may be subject to the development of settlements. The most perceptible manifestations develop directly above shallow sectors (several tens of meters below the surface). In these conditions, the weight of the overburden is insufficient to ensure complete recompaction of the caved in land during the years following the mining work. This results in the persistence of high artificial porosity close to the surface. Furthermore, the oldest mining works, because they tend to have irregular or even haphazard configurations, may be especially poorly caved or backfilled and have residual underground voids. If these voids are smaller in extension and volume, a failure inside these works can cause settlements (which in this case are also called "residual movements") that may be large in amplitude, on a scale of decimeters.	The phenomenon may be initiated several years or decades after the mine has closed down. The configurations required for this phenomenon make it. ***Infrequent***
Settlements by compaction/ consolidation of loose materials	These mechanisms are relevant to waste deposit structures, as well as open-pit mines and other backfilled mining structures. Mining waste, dry deposited in the form of mine dump or used for filling in old open-pit mines, may be fairly heterogeneous in composition, both in terms of material type and granulometry. The waste is often simply dumped with no guarantee of full compaction of the material. The same applies to backfilled shafts or access galleries. The materials dumped into these structures may consolidate and undergo significant compaction, which is likely to cause the formation of a depression on the surface.	The phenomenon may be initiated several years or decades after the mine has closed down, particularly under the effects of external disturbances. The configurations required for this phenomenon make it. ***Frequent***
Secondary compaction of loose land	Although it is exceptional, this mechanism occurs when the hydrogeological regime is altered by mining operations closing down, causing groundwater levels to change in land sensitive to secondary compaction (soft clays or peat, for instance) or to remobilization and migration (fine sands).	The phenomenon may be initiated several years or decades after the mine has closed down. The configurations required for this phenomenon make it. ***Very infrequent***
Ground heave	During deep mining operations, the surrounding land has been desaturated by drainage pumps used during exploitation. In certain configurations, resaturation of the land during flooding can result in a slow and very widespread ground heave throughout the previously drained area. The amplitude of vertical displacements observed can reach several decimeters. This phenomenon manifests itself by a rise, rather than a dip, in the surface ground. However, the initiating mechanism is more or less the same as that of settlement. The available experience feedback shows that these types of movements are very widespread in area (small curvature) and do not lead to visible effects on traditional buildings.	The phenomenon may be initiated several years or decades after the mine has closed down. The configurations required for this phenomenon make it. ***Very infrequent***

5.7.2. Settlement: hazard qualification

5.7.2.1. Qualification of intensity

The nuisances initiated by settlement result from the development of differential settlements (different amplitude from one point to another on a building foundation, infrastructure, etc.). It is mainly the vertical amplitude of these differential movements that governs the phenomenon's intensity, but because it is difficult to evaluate this amplitude, the maximum possible vertical amplitude of the settlement at a given point is generally used as a reference.

This type of disturbance is likely to cause deterioration to property on the surface (buildings and infrastructures) but is not likely to endanger people. With few exceptions, the intensity of the effects of settlement remain limited (on a scale of centimeters to decimeters).

Table 15: Settlement: intensity classes

Intensity class	Predicted amplitude
Very low	Amplitude on a scale of centimeters
Low	Amplitude on a scale of decimeters

5.7.2.2. Qualification of predisposition

Regardless of the mining context, two criteria govern a site's predisposition to the development of settlements:

- indications of past "settlement" movements (still visible on the surface or described in the archives) are present in a nearby sector with similar geological and mining characteristics;
- the presence of waste deposit structures, old open-pit mines and other backfilled mining structures, even if few indications are observed on the surface. The materials constituting these structures are generally loose and susceptible to being remobilized under the effect of overloading and external disturbances.

In the case of *waste deposit structures*, predisposition may be increased when:

- the deposit is very thick;
- the deposit is composed of materials that are prone to consolidation or compaction (clays or materials composed of very fine fractions are therefore more sensitive than sand, gravel or gravelly soil). Note that when there is a large inflow of water, fine sands may be suspended and remobilized;
- certain methods are used to create the deposit (simple dumping without compacting causes deposits with more voids, which are therefore more likely to shift).

Regarding land overlying *old mines operated using roof caving*, or *old improperly caved pillar mines*, the depth of the mining works is the main factor for predisposition to settlement. Generally, outside of specific configurations (a very thick area exploited, for example), mining works located at more than 50 meters in depth cannot cause settlements that are perceptible on the surface.

The mechanism of *secondary compaction* is rare and requires the convergence of two factors: first, a significant modification of hydrogeological conditions by mining operations (rise or variation in groundwater level); second, the presence of terrain that is sensitive to compaction or remobilization (peat, soft clays, fine sands in the case of remobilization).

5.7.3. Settlement: hazard mapping

The hazard map can vary depending on the scenario:

- limited to the waste deposit structure, or the backfilled open-pit mine or structure;
- corresponding to area of influence of caved or poorly stoped mines, which may have an angle of influence as described in the section on subsidence;
- limited to areas of terrain that is sensitive to secondary compaction.

5.8 Slope movements of loose materials: slides, superficial movements, flow slides

5.8.1. Description, mechanisms, effects

Slope instabilities are the types of disturbances most commonly observed on waste heaps or dumps built or excavated with or in loose materials (highly altered rock, soil, anthropogenic backfill, residue). These instabilities are actually a group of separate phenomena, the principal types of which are slides, superficial movements and flow slides.

Slides are the result of the movement of a landmass along a failure zone defined by a continuous surface (which may be circular, flat or sometimes complex in form).

The volumes involved depend on the depth of the failure zone. Thus, the term ***deep slide*** is used when the surface of the failure is located several tens of meters deep in the ground, and ***superficial slide*** is used when the surface is only a few meters deep.

The effects of a deep slide may be significant, since it can spread to the foot of the slope in the form of a cone and cause damage to any buildings or structures located there. It can also affect any buildings and infrastructures located on the top edge of the slope, near the slide's area of departure (also called the "landslide scar"). Thus, deep slides generally can only affect loose waste dumps, deposits or heaps of significant height (several tens of meters), which limits the number of potential cases.

Photograph 3: Deep slide of the Mieg waste heap, Pechelbronn mining basin, Alsace (image: GEODERIS)

The effects of a superficial slide, on the other hand, are much more limited, and only affect the slope itself or the areas at the foot and top of the slope. This phenomenon is much more frequent due to the very large number of smaller mining slopes and waste dumps.

The term ***superficial movements*** encompasses phenomena that are not associated with the presence of a well-defined surface failure: they may include creeping of soils or materials when their mechanical behavior is modified in the presence of water, or gullying in a slope caused by water.

Flow slides are movements where the slope consists of materials with no cohesion that remobilize in the presence of a large quantity of water. The material then transforms into a viscous fluid that flows at a high speed (generally between 1 and 7 m/s). This flow often has a stiff front composed of blocks of material and various debris. The term "debris flow" is often used in the field of natural mountain risks to describe the same mechanism, but involving much larger surface areas.

Flow slides are the most dangerous disorders likely to affect people and property located in the neighborhood of a slope. However, they are very rare, as they are linked to an abnormal or exceptional inflow of water (rainfall or anthropogenic).

5.8.2. Slope movements of loose materials: hazard qualification

5.8.2.1. Qualification of intensity

The main parameter used to evaluate intensity is the volume of material put into motion. The principal factors likely to affect this volume include: the type and granulometry of the materials constituting the slope, the slope's height, its steepness and morphology, the intensity of forecasted water flow, whether or not landscaping measures have been taken (e.g., covering, seeding).

In the specific case of *flow slides*, which are disturbances likely to cause damage to the safety of people and property located in their trajectories, it is not easy to identify a characteristic parameter that can be used to differentiate their consequences. Thus, we use the height of the flow of viscous fluids, since the phenomenon has high, indiscriminate kinetic energy.

Other factors can influence the flow's characteristics: the volume of material that can be mobilized, the steepness and morphology of the slope where the flow initiated, the steepness and morphology of the area of influence (governing the height of the flow), the presence of obstacles preventing the flow from spreading, etc.

The threshold values presented in the table below are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 16: Slope movements of loose materials: intensity classes

Intensity class	Description	Parameter and threshold value
Very low	Creep, gullying	Volume of a few m^3
Low	Superficial slides, large gullies	Volume of 10 to 100 m^3
Moderate	Deep slides	Volume of 100 to 5000 m^3
	Flow capable of damaging certain buildings and endangering road traffic	Flow height < 50 cm
High	Major deep slides	Flow height > 50 cm
	Flow with devastating consequences to people and property	Volume > 5000 m^3

5.8.2.2. Qualification of predisposition

The following factors contribute to increasing a slope's predisposition to slope movement:

- indications of past movements (still visible on the surface or described in the archives) are present in a nearby sector with similar geological and mining characteristics;
- presence of signs that a movement has already initiated (decompression cracks, bulging at the slope's foot, bent trees, rivulets, gullies, etc.);
- the nature of materials constituting the slope: type and granulometry of materials, presence of stratigraphic or tectonic discontinuities. The presence of materials containing a large proportion of fine particles, for example, will increase a site's predisposition to erosion and gullying;
- the topography, steepness and morphology of the slope;
- the nature, topography and hydrogeological conditions of the ground on which the deposit was formed (soft ground);
- potential modifications, either natural or anthropogenic, of local hydraulic conditions (weakening of the base of the slope in case of severe flooding affecting a watercourse at the foot of a slope, alteration of the system for draining or managing flow, creation of decantation basins, pipeline failure, blocked drains, runoff channels filled with fallen rock, etc.);
- the presence of aggravating factors such as the absence of adequate surface vegetation, the possible existence of dynamic stresses (e.g., earthquakes, vibrations), the development of certain human activities (mountain biking, motocross, overloading of the slope crest);
- the presence of old underground mining works underneath the slope, which may collapse and destabilize the slope;

On the other hand, when the land has been redeveloped or protective measures have been taken (covering, planting vegetation, adding supports, reshaping the slopes, etc.) this may decrease its predisposition to this event.

5.8.3. Slope movements of loose materials: hazard mapping

The map of this hazard must account for not only the slope, but also the areas at its summit and base that may be affected by the phenomenon. This is particularly the case for deep slides where the landslide scar is located at the summit and the area of influence is located at the base of the slope. When active slides are not observed in the field, the common practice, based on experience feedback and depending on the slope's morphology and the nature of its materials, is to use values expressed in fractions of the slope height H, both for the base of the slope and, less frequently, the top of the slope. So values such as H/2, H/3 are frequently seen, depending on the case in question: the mapped area thus overlaps the sloped zone.

The area of influence at the base has a much larger area in the case of a flow slide, and primarily depends on the surface morphology at the foot of the slope. Depending on whether there is a flat area or, in contrast, a thalweg that can direct the flow by limiting it laterally but extending it longitudinally, the mapped area will be very different. Observation of the terrain and an accurate topography of the foot of the slope are important prerequisites for a useful hazard map in this case.

5.9 Rock slope movements: rockslides, rock falls

5.9.1. Description, mechanisms, effects

Slope movements in rock formations (principally the sides of old open-pit mines) are when rock masses of varying volume detach from the wall and propagate to the base of the slope.

Geological stresses and stresses linked to mining operations carried out on these slopes result in instability and failure planes that are compounded with existing discontinuities. These planes of varying origin contribute to detaching the rock mass in blocks that may vary in volume and geometry.

Photograph 4: Blocks broken off of rock face, Villeveyrac mining basin

Rock faces are subject to gravity and natural and climatic actions (rain, temperature variation, freeze/thaw cycles, wind, etc.), which act on the rock and its discontinuities, leading to a slow evolution of the rock mass. Moreover, these natural dismantling mechanisms may be triggered or amplified by:

- vegetation (root action in the rock's instability planes, wind action on tree movement or destabilization, etc.);
- human activities (earthwork, material extraction);
- seismic shakes.

Depending on the volume of falling rock, these movements are referred to as stone falls (<0.1 m^3), block falls (0.1 m^3 to 10 m^3), rock falls (10 m^3 to 10^4 m^3), or major rock falls (>10^4 m^3).

Regardless of the volume, falling rock masses are dangerous to humans located within the area of influence. For volumes over 1 m^3, this type of phenomenon can also cause irreversible damage to property.

It is therefore essential to identify the extent of the area of propagation of the fallen rock, even approximately. Propagation depends on the volume of potentially unstable rock and the type and slope of the land at the foot of the cliff. A slope foot constituted of rock that is steeply sloped downward would be favorable to the propagation of blocks over large distances.

The more fractured the falling rock mass, the more it is likely to break into smaller blocks while falling, which can favor propagation downhill. Finally, the dimensions of the area of influence also depend on the type and kinetics of the movement that initiated the rock fall (e.g., toppling, slipping).

5.9.2. Rock slope movements: hazard qualification

In the context of natural risk prevention, the characterization of rock slope movement hazards is generally broken down into two mechanisms corresponding to the stages of development of a rock movement:

- the destabilization and initial mobilization of the rock (failure hazard);
- the movement of the rock masses along a certain trajectory until they stop (propagation hazard).

These two mechanisms are then combined into a "resulting hazard."

In the case of rock faces created by mining, which this handbook is concerned with, the hazard qualification was deliberately simplified. This is because the rock faces are generally smaller in height compared to natural slopes. There are some cases of deeper open-pit mines, but they are generally circular and confined in shape, which limits the propagation hazard at the bottom of the pit.

5.9.2.1. Qualification of intensity

The volume of falling material is used to define intensity classes. Depending on the volume of fallen material, this type of disturbance is likely to cause damage to the safety of people and property present on the surface.

The two main factors likely to influence the volume of falling material are the morphology of the rock face and the density of its discontinuities.

The threshold values presented in the table below are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 17: Rock slope movements: intensity classes

Intensity class	Description	Volume involved
Low	Stone fall	< 0.1 m^3
Moderate	Block fall	0.1 m^3 < v < 10 m^3
High	Rock fall	10 m^3 < v < 104 m^3
Very high	Major rock fall	> 104 m^3

5.9.2.2. Qualification of predisposition

The following factors contribute to increasing a rock slope's predisposition to failure:

- indications of past movements (still visible on the surface or described in the archives) are present in a nearby sector with similar geological and mining characteristics;
- indications of recent movements (e.g., fallen rocks on the ground, crumbling, fresh signs of breakage on the rock face);
- the geometry of the face: height, slope angle and discontinuities that may lead to instability;
- the discontinuity network affecting the rock mass is an essential factor. These discontinuities may be stratification joints, faults, fractures or contact points between the rock mass and the surface land. These discontinuities carve up the rock masses and facilitate their failure. There are different types, but the most frequent are: planar slides, dihedral slides (following a line where two discontinuity plans intersect), toppling, detaching, etc.;
- numerous external factors may play an aggravating role: the absence of a system for managing runoff water, climate events such as freeze/thaw cycles, dynamic stresses (e.g., earthquakes, mine blasting) or static stresses (overloading on the cliff's crest), etc.

5.9.3. Rock slope movements: hazard mapping

Just as with slope movements of loose materials, the map of this hazard must account for not only the slope, but also the areas at its summit and base that may be affected by the phenomenon.

The summit area may be affected by rock falls, especially major rock falls, since the hazard can be triggered within discontinuities that are visible on the slope but extend far into its upper edge.

The area at the base is affected by the propagation of the rock fall: the information phase (analysis of past instabilities) and the field survey of the distance of fallen rock from the slope are vital pieces of evidence. When active rock falls are not observed in the field, the common practice, based on experience feedback and depending on the slope's morphology, the nature of its materials and the density of discontinuities, is to use values expressed in fractions of the slope height H. So values such as H/2, H/3 are frequently seen, depending on the case in question.

The area of propagation below the fall is much larger if the surface at the base is sloped. Observation of the terrain and an accurate topography of the foot of the slope are important prerequisites for a useful hazard map. Trajectography software may be useful for more complex cases.

6 HAZARDS LINKED TO HEATING AND COMBUSTION IN MINING WASTE DEPOSITS

6.1 Description, mechanisms, effects

Sedimentary soils containing layers rich in solid carbon elements (e.g., coal, lignite, bituminous shale, peat) may be affected by in situ combustion, whether or not they have been exploited by mining work. These combustions may be triggered by the effects of mining or earthwork due to the self-heating induced by the oxidation of hydrocarbonate rocks coming into contact with the air (known as spontaneous combustion), or provoked by fire coming into contact with outcroppings (e.g., natural forest fires, stubble burning).

Rocky waste from the extraction of carbon mineral substances that is dumped on these mining sites (cinder coal, carbon shale, bituminous shale, etc.) is also subject to heating. This waste may spontaneously combust shortly after it is dumped (several months to several years), by self-heating of the fresh materials when their composition makes them particularly sensitive to oxidation (as is the case with certain more or less pyritic forms of coal); or later on, upon contact with fire on the sides of the waste deposits or after a period of prolonged exposure to a large amount of thermal solar radiation (dry periods).

Photograph 5: Discharging and spraying a burning waste heap, Gard mining basin

Depending on the context, combustion phenomena can vary greatly in duration, from several months to several decades.

The hazard study focuses on characterizing two potential effects of these phenomena: the ignition of brush fires or forest fires and accidental burns to humans at these sensitive sites.

- accidental burns to humans: the risk of burns to humans is high, and even higher when the combustion is superficial, primarily on the ventilated flanks of waste deposits. Multiple fatal accidents, both individual and collective, have occurred in the past;
- ignition of brush fires or forest fires: during dry periods or periods of high winds, the presence of burning materials near the surface is likely to ignite brush fires or forest fires that may have serious consequences, especially when located in the Mediterranean region.

Other dangerous phenomena may result from heating mechanisms:

Production of toxic and/or asphyxiating gases

The problems posed by the burning of old mining works or dumps primarily relate to the toxicity of combustion vapors containing gases that are toxic and/or asphyxiating (e.g., CO, CO_2, CH_4, SO_2, NO_x, H_2S, HCN), often malodorous (sulfurous products, tars, mercaptans), or contain trace metallic elements such as mercury, lead or arsenic. These vapors are sometimes produced in large volumes when the combustion site is superficial and well ventilated. Emissions may be more insidious (that is, difficult to predict) when the combustion is deep and the emitted gases diffuse toward the surface through cracks and fissures.

Production of explosive gases

Explosions of flammable gases that have issued from the combustion or pyrolysis of organic materials (H_2, CO, CH_4, hydrocarbons) and accumulated in cavities can also occur, both in the case of fires in underground mining works and in waste dump overheating. Explosions may be sufficiently powerful when they occur in contained spaces in abandoned mining works. They are less powerful and uncontained when they occur due to the inflammation of accumulated gases in small cavities or crevices formed on the flanks of coal mine waste dumps.

Ground subsidence or collapses

The reduction in volume of land affected by combustion causes subsidence or collapse of the overlying land, depending on the depth and size of the combustion source. Damage to property may be dramatic when these events affect buildings or roads.

Hydrogeological impact: mineralization of underground water

The natural lixiviation of coal-rich earth or coal deposits affected by the free combustion of mineral salts found in surrounding groundwater. Essentially, these are sulfates produced by the oxidation of pyrites, iron and magnesium oxyhydroxides, and arsenic issuing from arsenopyrite.

Heating and combustion can affect both underground mining works and waste deposit structures. In a hazard study, the potential effects of heating and combustion in underground mining works are studied as part of the "localized collapse" hazard, which is the principal possible consequence on the surface. The "heating and combustion" hazard is limited to mining waste deposit structures.

6.2 Waste deposit heating and combustion: hazard qualification

6.2.1. Qualification of intensity

Heating or combustion of a mining waste deposit structure is likely to cause damage to the safety of people and property present on the surface or in neighboring areas due to the risks of burning, gas emissions or fire ignition.

The volume of the material susceptible to combustion and the area of the impacted surface are the main influencing factors on the foreseeable consequences for the safety of the people and property present in the area of influence. Therefore, the parameters of volume and surface area may be used as representative values.

The hazard of waste deposit heating is commonly assigned a "moderate" intensity.

6.2.2. Qualification of predisposition

Old mining waste deposits created by the extraction of combustible rocks that remain unburned are predisposed to heating of the fraction of carbonaceous elements they contain [35].

A mining waste deposit structure's predisposition to heating depends on:

- observations or temperature measurements (using thermography, for instance) showing that a heating mechanism is affecting the structure;
- the presence of similar phenomena on other waste deposit structures, on the site or in similar or identical configurations;
- the type of materials constituting the waste deposit structure:
  - the forms of waste most predisposed to combustion are those known as mine dumps or pit dumps, constituted of "run of mine" substances issued from drilling galleries in the rock or coal, and of residue from cobbing extracted coal. They are composed of materials with a wide range of granulometry (0-200 mm) and highly diverse characteristics (gravelly blocks; more or less carbonaceous, bituminous and pyritic shale; coal; mine wood; miscellaneous waste of varying combustibility). Combustible materials make up 15 to 35% of pit waste composition;
  - wash plant dumps are composed primarily of shale-based materials with finer, more regular granulometry (0-20 mm). They may still contain significant proportions of carbonaceous materials, especially when the wash plants they come from are more modern. The ash content of wash plant waste dumps from before WWII was around 75%, versus 85% for more recent structures. Cases of combustion in waste dumps from modern wash plants are rare.

6.2.3. Waste deposit heating and combustion: hazard mapping

The hazard map includes the area of the waste deposit structure plus the margin of uncertainty for the structure's position and the margin of uncertainty for the map background.

7 HAZARDS LINKED TO MINING-INDUCED HYDROLOGICAL AND HYDROGEOLOGICAL DISTURBANCES

7.1 Origin of potential phenomena

Old mining works, at least the largest among them, have sometimes caused severe hydrological and hydrogeological disturbances and have modified, sometimes irreversibly, the morphology and structure of surface catchments, reservoirs and underground aquifers. This has led to the disruption of water flows, both underground and on the surface. These modifications were initiated during the mining operation phase, but continued after operations ceased (Figure 7).

The majority of *underground mining operations* were drained during extraction. The pumping led to a drawdown of the groundwater level, which resulted in the recession of nearby water sources or water supply wells, and even the modification of the flow of surface watercourses.

At the end of the operation period, the pumping stops, leading to a gradual flooding of the mining works (over a period of several months to decades or even a hundred years) and a rise in the hydrostatic level. Natural draining toward the surface occurs at topographical low points (valleys, depressions), often through mine galleries that connect to the surface. New discharge outflows can also appear.

In some large mining areas that ceased to operate at the end of the 20th century, flooding is currently in progress, and pumping has been done to avoid the future flooding of topographical low points and/or contamination of nearby surface aquifers used for human water supply by water from mining reservoirs.

Whatever the scenario, it can be assumed that the hydrostatic level in the area of a former mining operation is not in its original position.

In the case of *open-pit mines*, the impact is primarily on water flows on the surface where the topography has been heavily altered. Where the excavation was deep enough to reach the groundwater, pumping may have been done.

In most cases, the pit is partially backfilled after operations have ended. The rise in groundwater level due to pumping cessation leads to the appearance of a water plane, if the groundwater level rises above the bottom of the pit or covers all or part of the backfill. This water plane may or may not have a visible overflow.

However, it must be remembered that for these types of hazards, mining is not always the only cause. For example, over time, mining activity can contribute to a sector's economic development, which can then lead to very high industrial and communal water usage, thus contributing to the drawdown of aquifers. In such cases, how much the water level rises ultimately depends on both the cessation of water pumping and miscellaneous residual water consumption.

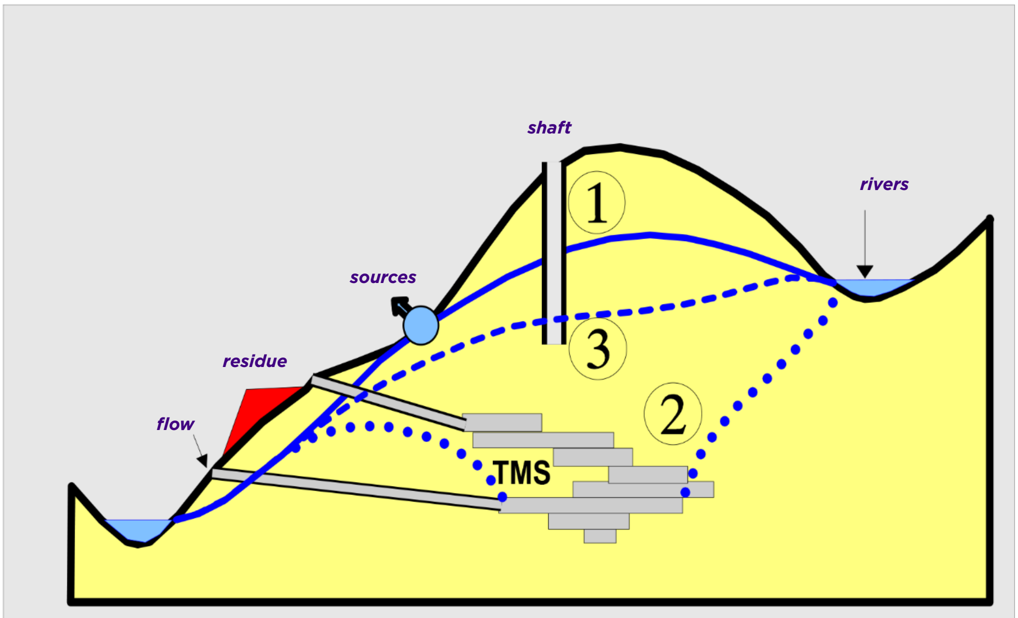

Figure 7: Conceptual diagram of the impact of underground mining operations on hydrodynamics during and after operation. (1) hydrostatic level before operation, (2) during operation, (3) after abandonment

7.2 Types and identification of potential phenomena

The main types of disturbances, which for the sake of simplicity will be grouped under the term "phenomena," are presented in Table 18 and detailed in this section.

As a reminder, this section only addresses hydrological and geological disturbances linked to the potential presence of water alone. Issues related to the environmental impacts of these mine waters are not covered in this handbook.

7.3 Modification of water discharge outflows

7.3.1. Description and mechanisms

Groundwater outlets, both natural (springs, resurgences) and artificial (wells or galleries connecting to the surface), can, due to modifications brought on by mining activity among other things, undergo various types of changes:

- simple modification of the characteristics of the outlet flow (e.g., increase or decrease in average flow, modification of the flow's distribution over time)
- reappearance of water outflows that existed before the mine and were dried up by mining operations. The characteristics of these renewed outlets generally differ from their former characteristics, particularly when the mining works have modified their outflow conditions (e.g., backfilling, plugging). It is not unusual for the water to reappear in a different location than the old spring;
- appearance of new discharge outflows. This happens especially in areas downstream from a hydrogeological drainage basin. A new outflow may result when a former mine connecting to the surface—usually through a gallery—is converted to serve as a runoff point for the mining reservoir. It can also take the form of a "natural" spring or resurgence appearing at a topographical low point. And in areas upstream of hydrogeological drainage basins, outflows that existed before the mine may not reappear after the mine has shut down.

In all cases, the phenomena observed can be explained by a rise in the piezometric level of underground water caused by the end of pumping operations. As a result of this rise in water level, areas that the mine had dried out or contributed to drying out become wet again.

Since these areas were modified, the new water circulations are often different from the old ones. They reuse the old flow paths, but also some new ones created by the mining operation, among other things (mining voids and fractured or caved rock with very high permeability). This establishes a new piezometric distribution in the subsoil different from that which existed before mining operations began.

Table 18: Principal mining-induced hydrological and hydrogeological phenomena

Type of "phenomenon"	Observed frequency (in France)	Brief description of mining area or configuration	Severity of disturbances (observed in France)
Modification of discharge outflows	**Very frequent**	Any mining area where mining operations required water pumping Presence of topographical low points and new discharge outflows from mining structures	Low
Flooding of topographical low points	**Infrequent**	Mining operations that generated large-volume voids over extended territories. The hydrostatic level intersects with the topography (which may have been altered by mining-induced ground movements). Connections between water in underground mining reservoirs and aquifers on the surface may be an aggravating factor.	High when low points have been transformed by human activity
Modification of watercourse flow regime	**Infrequent**		Varies depending on watercourse usage
Sudden flooding	**Very infrequent**	Natural or anthropogenic obstruction of new mining discharge outflows. Sudden failure of these obstructions	High if the areas downstream of these outflows have been transformed by human activity

Photograph 6: Resurgence of slightly salty water from a salt dissolution mine in Franche-Comté

The new flow regime that is established in a former mining area does not necessarily have the same permanence as a purely natural flow regime. In fact, the environment may undergo changes over time (collapse of mine voids, mobilization of preexisting discontinuities such as karsts or faults, physical-chemical phenomena—such as dissolution-precipitation, among others—that modify the permeability and geomechanical qualities of the subsoil). Without a doubt, the most critical situations are found in areas where soluble substances were mined (salt and potash), where it is very difficult to guarantee that the flow regime observed at a given moment is a stable one.

7.3.2. Modification of discharge outflows: hazard qualification

7.3.2.1. Qualification of intensity

Flow rate is the parameter used to determine intensity classes for the phenomenon of surface water resurgence.

The principal factors that can influence the value of this parameter include: the surface of the drainage basin from which the outflow is draining; difference in level in the drainage basin, which influences the hydraulic gradient, which drives underground flow; the volume of the mining reservoir and its capacity to act as a buffer to water flow (flood peak reduction); the hydraulic characteristics of the water outlet (dimensions, presence of flow obstacles).

The threshold values presented in the table 19 are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 19: Modification of water discharge outflows: intensity classes

Intensity class	Description	Value Flow rate in dm^3/s
Low	Seepage	<1
Moderate	Small stream	<10
High	Large stream	<100
Very high	Extreme resurgence	>100

7.3.2.2. Qualification of predisposition

The determining factor that influences a site's predisposition to the appearance of new water outflows is the establishment of an equilibrium of the piezometric surface of the groundwater level below the low areas of the topographical surface. If the groundwater table stabilizes beneath the level of the topographical low points, it will then drain toward another underground drainage basin, and the probability that resurgences will appear in the sector of study can be considered as zero.

In the presence of this determining factor, several other factors are favorable to a site's predisposition to the appearance of resurgences:

Presence of indications of former water sources that existed in immediate proximity to the mine before operations began
Presence of mining structures connecting to the surface and the underground reservoir
Presence of natural heterogeneities (highly permeable areas, faults, fractures, karstic galleries, etc.) that are likely to act as preferential drains

7.3.2.3. Hazard mapping

The hazard map must include, at a minimum and at the appropriate scale:

- the position of former water sources that may potentially be reactivated;
- the surface area of zones at risk for the appearance of new water outflows, highlighting any natural discontinuities that may be favorable to the phenomenon (faults, fractured or altered zones, etc.) and indicating, where possible, a range of expected flow rates.

7.4 Flooding of topographical low points

7.4.1. Description and mechanisms

A rise in groundwater level resulting from the end of pumping operations can sometimes bring the water level very close to the ground's surface, and can temporarily or even permanently exceed the topographical level.

In the first case, potential disturbances or nuisances can affect structures built partially or completely under the surface (e.g., basements, parking garages, underground networks, tunnels, sewers, underground or semi-underground passages). These become flooded, either permanently or for part of the year, depending on their depth and seasonal fluctuations in the groundwater level.

In the second case, the low-lying land itself, as well as the buildings or infrastructures built on it, become temporarily or permanently flooded.

Photograph 7: Wet area caused by rise in groundwater level influenced by mining

The mechanisms that cause this type of disturbance are largely similar to those that cause new water outlets to appear (rise in the piezometric level due to the end of pumping operations, modifications to flow regimes of underground water).

One aggravating factor, which can arise in large mining areas where regional aquifers are overlaid on former mining works, is a connection between these aquifers and the mining reservoir.

Regardless of the possible causes or interactions, it is low-lying areas (such as valleys) that are most sensitive to flooding. Areas of subsidence from old mines, which are often in the form of enclosed topographical depressions, can also be affected by floods.

Seasonal fluctuations in underground water levels can cause the areas affected by this phenomenon to dry out during certain periods of the year. They can dry out more easily when the layers of earth in the shallow subsoil have good drainage capabilities. On the other hand, a subsoil with very low permeability is a factor that predisposes the area to more lasting effects from this type of disturbance.

Finally, in areas where preventive measures have been taken against these nuisances by reducing the groundwater level through pumping, the hazard study should include an analysis of the potential for the failure of the pumping stations, which may lead to flooding.

7.4.2. Flooding of topographical low points: hazard qualification

7.4.2.1. Qualification of intensity

The parameter used to determine intensity classes is the minimum depth of the groundwater in relation to the surface, factoring in the seasonal variability of that depth.

Intensity classes are differentiated based on usage restrictions for the subsoil. We consider the intensity to be zero when the groundwater is deeper than 20 m, based on the principle that even though in certain very rare cases structures can exceed that depth, detailed hydrogeological studies would be done in those cases.

The threshold values presented in the table below are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 20: Flooding of topographical low points: intensity classes

Intensity class	Description	Value Groundwater depth (in m)
Very low	Exceptionally deep structures affected	10 to 20
Low	Deep structures affected	3 to 10
Moderate	Basements and underground networks affected Land parcels seasonally impassable	1 to 3
High	Any structure in the subsoil affected Intermittent or permanent presence of an open water plane	<1

7.4.2.2. Qualification of predisposition

The following factors affect predisposition to this hazard:

Presence of natural low points in the topography, potentially influenced by mining subsidence;
Presence of permeable ground at the surface that does not impede seasonal rises in groundwater levels and potentially increases the drainage rate;
Conversely, the presence of poorly draining ground at these low points, which can impede water evacuation after the fact.

7.4.2.3. Hazard mapping

The hazard map must include, at a minimum and at the appropriate scale:

- the position of former water sources that may potentially be reactivated;
- the area of zones at risk for the appearance of new water outflows;
- the outline of potential flooding zones;
- isovalue curves for the depth of the high groundwater level mark, distinguishing between the areas of depth based on the intensity classes assigned to this hazard.

7.5 Modification of watercourse flow regime

7.5.1. Description and mechanisms

Transfers of water between ground and surface water occur naturally. The direction of these exchanges depends on the relative position of the water levels between the watercourse and the groundwater. Watercourses drain the groundwater when the groundwater level is higher than that of the watercourse. In the opposite case, the watercourse refills the groundwater.

Environmental modifications induced by mining activity, then by the mine's shutdown (end of pumping operations) may modify the direction and/or flow of the groundwater-river exchanges. Broadly speaking, the effects of these modifications on the watercourse flow regime can result in opposite forms of disturbances:

- an increase in the average flow of watercourses and flood flows;
- a decrease in dry-weather flow.

The impact of the flow regime modification can extend well beyond the sector of the mining operation and the areas immediately surrounding it. It can affect the portion of the hydrographic basin located downstream from the mining site.

7.5.1.1. Increase in watercourse flows

The dewatering system used during mining operations may have contributed to decreasing the flow rates of certain watercourses that had originally been supplied by natural groundwater drainage points. Since mining operations were generally developed over several decades, the natural extension of the low-flow channels of affected waterways, as well as the flood zones that go with them, gradually fades from collective memory. In these conditions, the following events can occur:

- the watercourse's natural low-flow channel is adjusted or redirected under the pressure of human activity;
- the land is reshaped for development purposes within the flood plain—the natural overflow zones—or even in the natural low water bed.

The new drainage regime after pumping has ended may contribute to increasing the average flow rate of certain watercourses, thus leading to an increase in flooding rate and frequency that is incompatible with the new developments.

This increase stems from one or a combination of the following causes:

- development works on the surface have increased the size of the drainage basin;
- the creation of mining voids has increased the surface of the underground drainage basin drained by the watercourse;
- the end of pumping operations has led to a general rise in groundwater levels, which makes it likely to be drained by the watercourse at its low-flow level and through the springs that discharge into it;
- the new water circulation regime post-pumping may concentrate all underground water flows toward a reduced number of runoff points, thus increasing the surface of the drainage basin supplying a single watercourse.

In high water periods, the increase in size of the surface and/or underground drainage basin may lead to an increase in floodwater volume. Moreover, the presence of a network of galleries facilitates the flow of water in considerable proportions in the subsoil; this reduces the time it takes for the water to transfer between the groundwater and the watercourse, which then increases the speed and rate of the water's rise and the peak flood rate.

7.5.1.2. Decrease in dry-weather flow

In contrast to the phenomenon of increased flow in certain rivers, the new water circulation regime can also contribute to reducing the flow of other watercourses. This phenomenon leads to a decrease of the available water resources in the watercourse itself or a potential alluvial water table beneath it. This can have an impact on the volume available to supply water for various uses.

Other consequence may include:

- drying out of waterholes dug in the alluvial water table, or even drying out of the watercourse itself;
- decreased water quality, endangering aquatic ecosystems.

The decrease by varying degrees of the average flow rate of watercourses may stem from one of the following causes, or several of them combined:

- development works on the surface that have decreased the size of the drainage basin on the surface by directing a portion of the runoff to another drainage basin;
- the presence of mining voids, causing a portion of the groundwater, previously drained by the watercourse, to flow to a different drainage basin;
- the watercourse's water supply is cut off when pumped drainage water is discharged on the surface.

7.5.2. Modification of watercourse flow regime: hazard qualification

7.5.2.1. Qualification of intensity

For an *increase in watercourse flow rate*, the parameter used to differentiate intensity classes is the maximum flood rate of the watercourse, which has an impact on the extension of the flooded zone. This parameter is combined with the frequency of flooding in comparison to the mining period, which is used as a reference situation. Factors influencing this parameter are weather, the size of the drainage basin and any water flow management measures taken when the mine was closed down.

There are two intensity classes distinguished based on the damage caused to land use and the danger to property.

Table 21: Modification of watercourse flow regime (increase in flow rate): intensity classes

Intensity class	Description	Value
Moderate	The watercourse exceeds its low-flow channel only occasionally	-
High	The floodplain is regularly flooded	-

It is especially important to determine whether the expected flood flow increase linked to old mining works is likely to contribute more or less significantly to the development of floods in comparison to a context where no mining works are present.

For a *decrease in baseflow*, the intensity parameter used is the flow rate of the watercourse at its minimum flow, combined with its duration. Just as in the case of increased flow, the intensity factor is linked to climatic data, the size of the drainage basin and how water flow was managed after mining operations ended.

Table 22: Modification of watercourse flow regime (decrease in baseflow): intensity classes

Intensity class	Description	Value expressed as variation in the baseflow rate in comparison to rate during mining operations
Very low	Influence on the baseflow rate is negligible	Variation < 50%
Low	The baseflow rate is visibly influenced during dry periods	Variation > 50%
Moderate	The flow may cancel out during dry periods	Variation ~100%

7.5.2.2. Qualification of predisposition

The following factors affect predisposition to the hazard of *increased water flow rate*:

Extension of the alluvial plain with the presence of a shallow water table that may easily overflow (this phenomenon may be amplified by a rise in the water table upon mine closure)
Modification of the topography of the floodplain under the effects of past or future mining subsidence
Developments that could disturb the circulation of waterways that may have developed during the mining phase when the flow was reduced (traffic routes, constructions, waste dumping, non-maintenance of riverbanks)
Method used for water management after mine closure, possibly leading to the concentration of the mining works' natural drainage into a reduced number of discharge points

For a *decrease in base flow*, the essential predisposition factor is the presence during the mine's operation phase of dewatering discharge, artificially supplying the watercourse flow and allowing for a modification in water usage (use of the resource or dilution of effluents). The phenomenon is aggravated if the watercourse is only slightly supported by the aquifer system, or especially if the watercourse feeds into the groundwater.

7.5.2.3. Hazard mapping

The map should include the hydrographic network, particularly the sections of the river where the high and low water levels will be affected by the consequences of mining works. For increases in flow, try to give a representation of the potential flooding areas by qualifying the water's contours in terms of predisposition.

7.6 Sudden flooding

7.6.1. Description and mechanisms

The phenomenon of sudden flooding results from the sudden emission of a very strong flow of water or mud through an orifice in connection with an inundated mining reservoir. Depending on the flow rate and volume of discharged water, the effect can be more or less devastating and can range from a simple water level rise in a riverbed to a sweeping, highly destructive wave.

The phenomenon's intensity is linked to the volume of water likely to discharge, the hydrodynamic characteristics of the evacuation outlet and the morphology of the terrain enabling downstream flow. As a rule, the consequences are all the more severe as the phenomenon can develop in a site where the downstream zones are occupied by human activity.

The initiating mechanisms of this phenomenon may result from multiple natural or artificial causes, albeit ones that require rather specific topographical configurations.

The most common situation is that of a mining reservoir at altitude that was created as a result of the intentional or unintentional plugging of mining orifices at lower topographical points that previously provided drainage. The failure of an artificial plug or the run-out of a collapsed gallery or plugged karst can then quickly lead to flows and consequences that are more severe the higher the load behind the plug and when the reservoir is of sufficient volume for the phenomenon to last several days.

Another situation may result from a karstic reservoir spilling into mining works, leading to a sudden overflow at the mine's discharge outlets.

There is also a risk of a wave forming when large inundated mining voids suddenly collapse.

Finally, in the case of an old open-pit mine that formed a mine lake, or in the case of an underwater residue dump, there is the possibility of mechanical instability leading to the slippage of a large mass of materials within the contained area or the failure or a dyke, which causes a sheet of water and mud to spill over downstream from the structure.

7.6.2. Hazard qualification

7.6.2.1. Qualification of intensity

The phenomenon manifests in a sheet of water flowing with a certain speed for a variable duration. In the absence of a unique parameter for the intensity of the physical phenomenon, we will define intensity classes based on its effects on people and property, using a simple value indicating the height of the floodwater, and based on the principle that the flow speed always reaches a dangerous value.

The factors influencing intensity are the capacity of the mining reservoir that may potentially be emptied, the hydraulic conductivity of access points between the reservoir and the surface, and the capacity of the receiving environment to evacuate a sudden, intense flow of water.

The threshold values presented in the table below are for information purposes only. They can be adapted to a given context by the expert in charge of hazard evaluation.

Table 23: Sudden flooding: intensity classes

Intensity class	Description	Value Water height
Low	Water flow capable of heavy local erosion but with no damage to buildings or danger to people or vehicles	< 20 cm
Moderate	Flow capable of damaging certain buildings and endangering local road traffic	between 20 cm and 50 cm
High to very high	Devastating water flow	> 50 cm

7.6.2.2. Qualification of predisposition

The key predisposition factor is the presence of a mining reservoir susceptible to sudden evacuation at the surface. This reservoir forms naturally in deep mining works, underneath their drainage area, but it can also be situated above potential discharge outlets, having been formed intentionally upon the mine's closure by plugging openings on the surface, or appear spontaneously due to the plugging of drainage conduits following a collapse. Depending on the case, the aggravating factors for this hazard include:

Impossibility of monitoring or maintaining plugs
Impossibility or absence of monitoring water level in mining works
Risks of instability of mining works that may lead to a mass collapse
Possibility of inadvertent overfill of the mining reservoir by a flooded karst
Presence of limestone terrain that may contain plugged karstic conduits, which may connect to the mining works

7.6.2.3. Hazard mapping

To map this hazard, try to identify all emission points (gallery and shaft openings, low points of a natural or artificial dyke, waste heap in a valley, etc.) that are likely to produce a sudden, intense flow; and specify as much as possible the presumed contours of the affected area downstream of the sheet of water.

8 HAZARDS LINKED TO GAS EMISSIONS FROM MINES

Ineris created a methodological handbook in 2016 dedicated to the detailed evaluation of mine gas hazards [6]. Here, we will present a very brief summary; we recommend that the reader consult that handbook for more information.

8.1 Description and mechanisms

This phenomenon occurs when gas from a mining operation rises to the surface. It is likely to present dangers primarily to people and, more rarely, to property or the environment. These dangers include fire, explosions, asphyxiation and intoxication.

The gases may be endogenous (originating inside the deposit before mining—chiefly methane and its higher homologues, and carbon dioxide) or exogenous (originating in the external environment that was disturbed during and after mining). The gases most frequently encountered in a post-mining context are carbon monoxide, carbon dioxide and hydrogen sulfide.

Abandoned underground mines are most likely to feature the three main elements necessary to provoke this potential phenomenon:

- the presence of residual voids constituting a more or less confined and connected underground reservoir. These voids may have been created directly by mining or appeared in the surrounding earth as a result of a mining operation;
- the presence of dangerous gases or oxygen-deficient atmospheres;
- the possibility of production and/or accumulation of these gases in significant quantities and their migration toward the surface in dangerous concentrations.

Abandoned underground mines give rise to three main environmental modifications:

- the creation of residual voids originating from mining works and mining infrastructure (e.g., galleries, shafts). The volume of these residual voids depends on the size and type of the mine;
- the degradation of the overburden of old mining operations, which increases its fracturing and/or porosity and facilitates the migration of fluids (water and gas; gas may originate from mining or be produced by another geological formation in the overburden and then reach the surface through the fractures caused by mining activity);
- the alteration of hydrogeological conditions after underground mining has ended; most commonly in the form of a drawdown in aquifer levels. This facilitates the migration of gases in the post-mining voids and the overburden.

These modifications directly favor the release, production, accumulation and circulation of gases within rock masses.

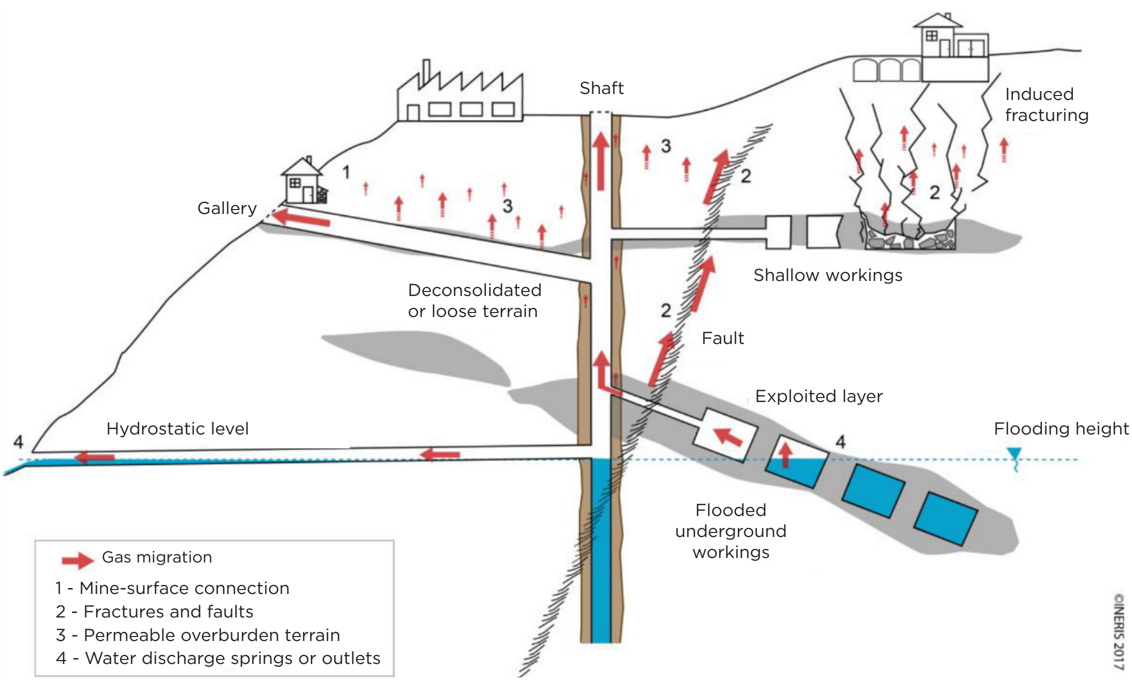

Figure 8: Principal migration paths of mining gas emissions

8.2 Gas emissions: hazard qualification

8.2.1. Qualification of intensity

Intensity is expressed as a convergence of two factors:

- the aptitude of the mining reservoir to produce or contain dangerous gases (in terms of composition and quantity);
- the potential volume of the flow of these gases toward the surface.

Dangers to property or infrastructures exist only when the mine gas is flammable, since its accumulation can lead to a fire or explosion. However, since people would also be exposed in such a scenario, the phenomenon's intensity is qualified only in terms of the danger it poses to people.

The intensity classes, as established in the 2016 handbook[4], are as follows:

Table 24: Mine gas emissions: intensity classes

Intensity classes	Characteristics of gas emissions within mining voids
Low	Emission containing: - either flammable gases at concentrations lower than the Lower Explosive Limit (LEL); - or asphyxiating or toxic gases at concentrations that exceed the Reference Concentration Limits (RCL), but only result in a slight and reversible effect.
Moderate	Low to medium emission containing: - either flammable gases at concentrations greater than or equal to the LEL; - or asphyxiating or toxic gases at concentrations that may have an irreversible effect; or: Low emission containing asphyxiating or toxic gases at concentrations that may have a lethal effect;
High	High emission containing: - either flammable gases at concentrations higher than or equal to the LEL; - or asphyxiating or toxic gases at concentrations that may have an irreversible effect. Medium to high emission containing asphyxiating or toxic gases at concentrations that may have a lethal effect.

4. We recommend that the reader consult the Ineris handbook for more information on evaluating intensity and threshold values (RCL, LEL)

8.2.2. Qualification of predisposition

A post-mining site's predisposition to producing surface gas emissions is expressed by the properties of the environment surrounding the site which enable (or limit) the migration toward the surface of gases present inside old mining works and the surrounding earth.

When evaluating predisposition, two principal migration paths should be considered:

- migration of gases through the overburden, including any discontinuities in that land formation;
- migration through mine structures connecting to the surface.

Gas migration can occur in the form of gas dissolved in water. It should therefore be considered as part of the study of structures connecting to the surface, since in the majority of cases, gases are only released from mining water through discharge from mining structures.

Regarding the *overburden*, the primary factors to take into consideration in relation to aeraulic resistance (resistance to gas flow), are as follows:

- overburden thickness: all things being otherwise equal, the thicker the overburden, the more resistant it is to the flow of gas toward the surface;
- the influence of mining operations, which may have weakened, fractured and/or increased the porosity of the overburden, thus facilitating gas flow;
- the presence of specific geological formations that may increase aeraulic resistance (e.g., highly impermeable rock layers, perched groundwater);
- or, on the contrary, the presence of highly permeable geological formations or discontinuities that may act as preferential drains for gas;
- geomechanical instabilities in the overburden, which may facilitate gas flow.

Structures connecting to the surface constitute single points through which mine gas migration may potentially be facilitated, even if the openings were treated and closed after the mine shut down.

In this case, the structure's aeraulic resistance is also used as the determining factor in qualifying its predisposition to mine gas migration. Nonetheless, the potential instability of these structures should also be considered, since it may have an effect on surface gas emission (backfill run-out, collapses).

The type of the structure, the volume of any voids within it, and the type and permanence of its backfill and/or closure are important criteria. Because multiple factors may augment or limit a structure's predisposition, each structure must be subject to an individual analysis.

8.3 Gas emissions: hazard mapping

In the case of *migration through the overburden*, the perimeter of different hazard zones overlying former mining works is defined first by a vertical projection of the geometric limits of the mining works in question.

Secondly, the influence of the mine itself is considered, based on the type of ground movements which have occurred, or which may occur. This so-called "geomechanical" influence can laterally modify the aeraulic characteristics of the overburden and make it more permeable, and thus more favorable to gas migration.

In the case of migration through *mine structures connecting to the surface*, the structure's area of influence must be taken into account. This should include:

- any connections to other structures on or below the surface;
- the presence of leaks in the seal of a structure;
- the state of fracturing in the ground surrounding the structure;
- the margin of influence linked to a potential ground movement, if such a hazard is relevant.

9 REFERENCE DOCUMENTS

[1] Collectif, INERIS, 2006. L'élaboration des Plans de Prévention des Risques Miniers. Guide Méthodologique. Volet technique relatif à l'évaluation de l'aléa. Les risques de mouvements de terrain, d'inondations et d'émissions de gaz de mine. INERIS-DRS-06-51198/R01, http://www.ineris.fr/guide-pprm

[2] GEODERIS, 2012. Guide pratique pour l'homogénéisation des études détaillées des aléas miniers Volet "effondrement localisé." GEODERIS N2012/010DE

[3] GEODERIS, 2015. Bassin houiller lorrain. Évaluation de la prédisposition de présence de crevasses. GEODERIS E2015/062DE

[4] INERIS, 2010. Note d'information sur la nature des mouvements de terrains susceptibles de se développer à l'aplomb des anciennes exploitations menées par chambres et piliers dans le bassin houiller de Provence. INERIS DRS-10-116224-09341A

[5] INERIS, 2015. Retour d'expérience sur les effondrements localisés miniers. INERIS DRS-15-149489-10509A, http://www.ineris.fr/centredoc/drs-15-149489-10509a-fina-unique-1446806603.pdf

[6] INERIS, 2016. Évaluation de l'aléa "Gaz de mine." Guide méthodologique. INERIS-DRS-15-149493-10366B, http://www.ineris.fr/centredoc/alea-gaz-de-mine-guide-ineris-2016-1457701762.pdf

[7] INERIS, Cerema, GEODERIS, 2017. Post-Mining Risk Management in France. Ineris- DRS-19-178745-02406A.

10 BIBLIOGRAPHY

[8] ARCAMONE J., 1980. *Méthodologie d'étude des affaissements miniers en exploitation totale et partielle.* Doctoral thesis from the Institut National Polytechnique de Lorraine, École des Mines de Nancy

[9] BRGM, 1980. *Fiches signalétiques de digues à stériles concernant quelques exploitations minières françaises.* BRGM n° 80 SGN 433 GEG

[10] BRGM, 2008. *L'élaboration des Plans de Prévention des Risques Miniers. Guide méthodologique. Volet technique relatif à l'évaluation de l'aléa "Pollution des sols et des eaux."* BRGM/RP-55143-FR

[11] CHAUVIN R., LODEL R., PHILIPPE J. L., 1986. Combustion spontanée du charbon. Revue de l'Industrie Minérale, *Mines et carrières*. Les Techniques, p.71-77

[12] CSTB, 2004. *Bassin minier nord-lorrain. Étude des conditions de constructibilité dans le bassin sidérurgique et ferrifère nord-lorrain.* No reference number

[13] CSTB, 2011. *Guide de dispositions constructives pour le bâti neuf situé en zone d'aléa de fontis miniers.* Reference no. 26029541

[14] DE LA GOUPILLIERE H., 1920. *Cours d'exploitation des Mines*. 5 volumes. Paris Dunod Editor

[15] FINE J., 1993. *Le soutènement des galeries minières.* ARMINES Editions

[16] FLAGEOLLET J.C., 1989. *Les mouvements de terrain et leur prévention.* MASSON Editions Collection Géographie

[17] GEODERIS, 2015. *Note relative à la constructibilité dans les zones d'aléa "effondrement localisé" de niveau faible.* REPORT N2015/015DE – 15NAT23010

[18] INERIS, 1996. *Méthodologie pour la connaissance et l'identification des risques de mouvements de terrain.* SSE-JTr-CDi/CS-95-21EP37/R01

[19] INERIS, 1997. *Guide méthodologique pour l'arrêt des exploitations minières souterraines. Traitement des puits, galeries et descenderies abandonnés.* INERIS-SSE-CDi/CS-97-22EP46/R04

[20] INERIS, 2001. *Guide méthodologique pour l'arrêt des exploitations minières souterraines.* INERIS-DRS-01-25750/R01

[21] INERIS, 2005. *Évaluation des aléas liés aux feux souterrains dans les anciennes exploitations de charbon.* INERIS – DRS – 05 – 55108/R01

[22] INERIS, 2005. *Contribution au développement d'outils d'aide à l'évaluation des aléas dans le cadre des PPRM Aléa "mouvements de terrain" pour les gisements pentés et filoniens.* Partie 2: Typologie des événements redoutés au droit d'exploitations pentées et/ou filoniennes. INERIS-DRS-05-55102/R02

[23] INERIS, 2009. *Annexe technique au guide d'élaboration des Plans de Prévention des Risques Miniers. Évaluation de l'aléa "effondrement localisé."* INERIS DRS-09-103953-12226A

[24] ISRM, 2008. *Mine closure and post-mining management. International state-of-the-art.* No reference number

[25] JEGER C., 1976. Étude des conditions de naissance des combustions spontanées dans les houillères françaises. Revue de l'Industrie Minérale, *Mine, May,* p.116-140

[26] KAMBRI S., 2015. *Étude des crevasses minières du bassin ferrifère lorrain : évaluation des critères de prédisposition d'apparition et analyse d'intensité.* Master's thesis. University of Lorraine, École Nationale Supérieure des Mines de Nancy

[27] KRATSCH, H., 1983. *Mining subsidence Engineering.* Springer Verlag, Berlin, Heidelberg

[28] LCPC, 2000. *Caractérisation et cartographie de l'aléa dû aux mouvements de terrain.* Collection Environnement. Les Risques Naturels

[29] LCPC, 2004. *Les études spécifiques d'aléa lié aux éboulements rocheux.* Collection Environnement. Les Risques Naturels

[30] LCPC, INERIS, MATE, 2002. *Guide technique d'évaluation des aléas liés aux cavités souterraines.* Collection Environnement – les risques naturels. Laboratoire des Ponts et Chaussées

[31] LIN S., WHITTAKER B.N., REDDISH D.J., 1992. *Application of assymetrical influence functions for subsidence prediction of gently inclined seam extractions,* Edition Elsevier

[32] MATE, METL, 1999. *Guide méthodologique pour l'élaboration des Plans de Prévention des Risques naturels (PPRN). Risques de mouvements de terrain.* French documentation

[33] MICHALSKI E.R., OUVRY J.F., WOJTKOWIAK F., 1997. Aspects hydrauliques des ouvrages de retenue des résidus industriels fins. *Mines & Carrières* – Les Techniques, special issue Digues & Terrils, November 1997. Editions de la Société de l'Industrie Minérale

[34] PAQUETTE Y., HANTZ D., 1997. Terrils et verses minières. Conception, surveillance, réhabilitation. *Mines & Carrières* – Les Techniques, special issue Digues & Terrils, November 1997. Editions de la Société de l'Industrie Minérale

[35] PAQUETTE Y., 1997. La combustion des remblais houillers et crassiers sidérurgiques. *Mines & Carrières* – Les Techniques, special issue Digues & Terrils, November 1997. Editions de la Société de l'Industrie Minérale

[36] PAQUETTE Y., LAVERSANNE J., 2003. *Guide du détenteur de terrils et autres dépôts miniers issus de l'activité charbonnière (verse, bassins de décantation, dépôts de cendres).* Les fascicules de l'Industrie Minérale

[37] PIGUET J.P., WOJTKOWIAK F., 2000. Affaissements et déformations au-dessus des exploitations minières : mécanismes et évolution dans le temps. *Mines & Carrières*. Volume 82, June 2000, p. 36-47. Editions de la Société de l'Industrie Minérale

[38] PROUST A., 1964. Etude sur les affaissements miniers dans le bassin du Nord et du Pas de Calais. *Revue de l'Industrie Minérale*, June-July 1964

[39] STRACHER G., PRAKASH A. et al. *Coal and peat fires: a global perspective.* Volumes 1 (2010), 2 (2012), 3 (2014) and 4 (2015), Elsevier

Crédits photos : Ineris (couverture, 15 ; 16 ; 20 ; 23 ; 29 ; 30 ; 35 ; 39 ; 41 ; 43 ; 44 ; 49) • GEODERIS (p. 34) • Piguet J. P. et Deck O. (p. 27) • Conception-réalisation : O'communication – Agence Les Récréateurs

Knowledge of hazards associated with mining works has largely been developed in recent years in metropolitan France. The research carried out to apprehend risks on the surface influenced by old mining operations is realised through a "hazard study", for the vast majority of the dreaded phenomena which can occur.

This handbook provides the framework and guidelines for this achievement.

In the framework of the risk management that these old mining works can generate, on the one hand, and the sustainable development of these territories, on the other hand, the study of the hazards, and associated maps, constitutes an essential step.

The objective is to map the zones where hazards exist and to evaluate their level, in order to determine the risk for existing stakes and the possibilities of construction or development in terms of land planning.

This key technical step allows the instructor services to develop post-mining risk management procedures, allowing local authorities to better know and adapt to the dreaded phenomena and land planners to better understand the conditions of constructibility.

This handbook provides information on post-mining phenomena, the feedback that has been established and indications on the parameters to be considered to evaluate and map the hazard.

French National Institute for Industrial Environment and Risks
Parc technologique Alata - BP 2 - F-60550 Verneuil-en-Halatte
+33 3 44 55 66 77 - ineris@ineris.fr - www.ineris.fr

INERIS
controlling risks
for sustainable development