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Abstract

Mining Risk Prevention Plans have been developed in France in order to deal with "Post-Mining" issues in a rapid and operational way. This inevitably implies that the final result of those risk analyses might contain a significant part of uncertainty. The study presented herein introduces a framework and some tools that allow experts to express the confidence they have in their evaluation and raise the main difficulties they face in their daily work.

Introduction

Many countries are now facing problems related to abandoned mines. The persistence of residual voids or the existence of open pits may generate disorders of several kinds: surface instabilities, surface flooding, noxious gas emission, severe environmental impacts, etc. Those disorders may have serious consequences on the populated mining areas. They also strongly influence the land use management of the concerned areas. In order to post and manage properly those hazards and risks, French Authorities have developed a technical and administrative powerful tool: the Mining Risk Prevention Plans (MRPP). MRPP aim to identify the most sensitive areas subject to "post mining hazards" and to define technical and regulation rules able to manage the principles of the future urbanism development on surface (Didier and Leloup, 2005).

As defined in the edicts n°95-1089 of October 5th 1995 and n°2000-547 of June 16th 2000 of the French law, a MRPP has to contain:

1. a notice presenting the region being studied, the nature and the importance of the hazards that are likely to appear, as well as their probability of apparition and their consequences, *given the state of knowledge*;
2. one or several graphical documents mapping hazards zones;
3. a regulatory zoning plan defining homogeneous zones in terms of prohibitions, instructions or recommendations concerning land use, for both existing and future projects.

In order to provide those 3 items and to deal with the regulatory constraint, MRPP are usually drawn up in 4 main phases (INERIS, 2004), summarized in Figure 1.

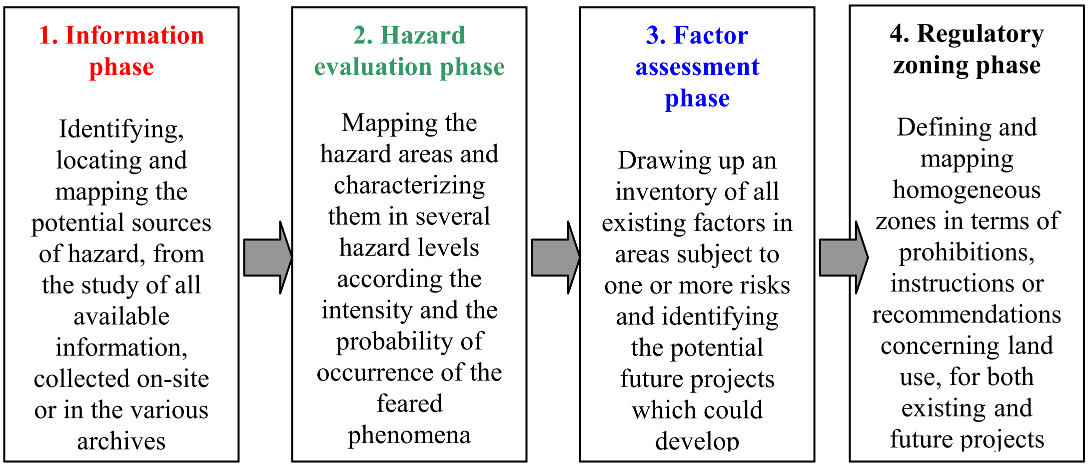

Figure 1. The main phases of drawing up a MRPP.

Identification of the main problems encountered while elaborating a MRPP

MRPP have been developed in the context of the difficult management of the “Post-Mining“ phase, the issues of which consist in posting and managing various risks likely to appear in numerous old mining sites spread in the whole French territory, at short notice and with limited financial and human resources. In such a context, MRPP have been developed to be rapid and operational tools for both population and Authorities. Therefore the philosophy of MRPP is to elaborate expert evaluation with available knowledge and to limit expensive investigations. The hazard assessment is thus mainly based on qualitative studies performed by experts using data collected in the field or in the various archives. As a matter of fact, the final result of the risk assessment might contain a significant part of uncertainty.

Working *given the state of knowledge* implies for the expert in charge of the evaluation to be limited by the quality of the information he can collect in the field or in archives. He usually has to face problems concerning the reliability of the mining maps (incompleteness, bad adjustment in comparison to surface, etc.), the informal nature of several data (oral statements, newspaper articles, etc.) or the difficulty to analyse events that occurred in the past (past collapse that is no more visible on surface at the time of the study, etc.).

The choice of elaborating simple (not simplistic) and rapid evaluations based on *expert opinion* implies to privilege qualitative methodologies of risk analysis rather than strong and complex modelling. Methods used by experts are principally based on *experience rules*, rules of thumb or are built on hypotheses that are sometimes very strong. The problem relies here in the degree of reliability of the methods being used and in the truth of the hypotheses that have been made.

Similarly, it is very difficult to deal with the regulatory request for expressing the probability of occurrence of hazards, introduced in the edicts n°95-1089 of October 5th 1995 and n°2000-547 of June 16th 2000 of the French law. This probability, denoted as *susceptibility* or *predisposition* is usually qualified in different levels: low, medium or high.

Proposals for the integration and the representation of uncertainties in MRPP

Hypotheses and steps of work. In this study, a methodology has been built in order to both deal with the problems that have been presented before and respect the concept of MRPP as a rapid and operational tool. This methodology may be presented in three steps, each of which is aimed at answering a precise question:

1. Does it exist on a specific location of the area being studied a potential source of hazard?
2. *Assuming* the existence of this source of hazard, can it generate a disorder or a harmful effect on surface and what is the reliability of this result ?
3. How to reduce or at least mitigate the risk?

Concerning the existence of a source of hazard. The first question, concerning the existence of potential sources of hazard, is basically relative to the confidence or trust of the expert regarding the data he collected. In the context of MRPP, concerning for example the problems of surface instabilities, the sources of hazard are clearly the old mining infrastructures (underground workings, shafts, etc.).

For the most recent mines, during the phase of its closure, operators were asked by the French Authorities to compile all the information about the workings, including the mining maps. However these maps may be of different qualities, incomplete or even false. Some maps have been drawn before the end of the mine and the real working limits may extend beyond the presumed ones. On the contrary some working areas may be mapped although they remained at a planning stage and they obviously do not contain any underground voids. On some other maps, pillars can be mentioned as “blasted” but numerous residual underground voids may still remain today, as for example in some old mining workings of the iron ore district of Lorraine, France.

The problem is far more critical for the older mines. The extraction have often been small scaled, chaotic and made by craftsmen. Maps are, most of the time, unusable for a purpose of risk analysis (inaccuracy, bad adjustment of maps with regard to surface, distortion) or they are even non-existent! Therefore, experts have to base their studies on *indications* of workings, as geology, existence of old surface collapses, oral statements, etc. Where ore deposits exist or where a surface collapse occurred, mining workings might have been developed. It is thus possible that sources of hazard still exist today in these sectors.

The confidence an expert can have in the real existence of a source of hazard is thus dependent on the quality of the source of information he used to identify it. It appears really interesting to characterize each of the information sources by a confidence level or an index of existence related to *the probability that a source of hazard really exists in a given area, taking into account the source of information that allowed to identify this one*. The higher this probability, the more reliable the information and so the more confidence we will have about the existence of a structure likely to generate an accident. Such an index may for instance be determined by a committee of experts used at drawing up the MRPP. An example is given in Table 1.

Table 1. Example of a grid of values for the index of existence, ranging from 0 to 5.

<table>
<tr><td rowspan="9">Mining map available</td><td rowspan="2">Partial extraction method</td><td colspan="3">Room-and-pillar</td><td>5</td></tr>
<tr><td colspan="3">Gallery (or other small voids)</td><td>5</td></tr>
<tr><td rowspan="2">Total extraction method</td><td colspan="3">Good quality of pillar extraction (cf. extraction method)</td><td>1</td></tr>
<tr><td colspan="3">Bad quality of pillar extraction (cf. mining map quality, extraction method)</td><td>3</td></tr>
<tr><td rowspan="5">Unknown extraction method</td><td rowspan="2">Extraction method of contemporary bordering workings</td><td colspan="2">Total exploitation</td><td>3</td></tr>
<tr><td colspan="2">Partial exploitation</td><td>4</td></tr>
<tr><td rowspan="3">Archives</td><td rowspan="2">Availability of data</td><td>Total exploitation</td><td>3</td></tr>
<tr><td>Partial exploitation</td><td>5</td></tr>
<tr><td colspan="2">No data available</td><td>3</td></tr>
<tr><td rowspan="4">No mining map available</td><td colspan="4">Favourable geology + existence of an old visible surface collapse</td><td>4</td></tr>
<tr><td colspan="4">Favourable geology + old surface collapse mentioned in archives</td><td>3</td></tr>
<tr><td colspan="4">Favourable geology OR old surface collapse</td><td>2</td></tr>
<tr><td colspan="4">Doubt on the nature of the surface collapse</td><td>1</td></tr>
</table>

NB : In this grid, the indexes of existence which are grouped into classes, concern the small sized underground voids that are able to generate sinkholes at surface. Values given are currently in phase of validation. (0 : 0-10% ; 1 : 10-30% ; 2 : 30-50% ; 3 : 50-70% ; 4 : 70-90% ; 5 : 90-100%).

Some precisions have to be established about the real signification of such a numerical index. An index of existence equal to 5 does not automatically mean that a hazard exists. It only means that the expert is confident concerning the fact that a mining infrastructure likely to create a disorder exists at a precise location of the studied area. The expert will have then to assess the hazard by using models and data about the geometry of the workings, etc. For instance, an index of 5 will be assigned to a 150m-depth mining gallery which is accessible and perfectly known. However, due to its important depth, the hazard due to this one is null.

Concerning the evaluation and the zoning of the hazard. The question about the existence of a source of a potential hazard leads automatically to another question: what can occur if this source of hazard really exists? In the example presented before, the answer was relatively obvious. We know, by experience, that if a small gallery located at an important depth collapses, the void will be filled in by the bulking of the overburden materials and no disorder will appear on surface. Even though it has not been explicitly expressed, this reasoning relies on a modelling process. The volume of the filled materials has been assessed in this case to be far greater than the volume of the initial void.

MRPP have been developed in order to deal with several mining-related risks: surface instabilities, water and soil pollutions, mine gas emission on surface, etc. The mechanisms of some of those risks are relatively easy to understand and modelling them is today possible, even using very simple analytical formulae. For the other kind of risks, we may hope that the researches that are currently undertaken will lead to the development of such models. Considering the risk of surface instabilities due to mining, simple models exist today to assess in an analytical form the amplitude of settlement, the height of caving for sinkholes, the slopes of the subsidence curves, the stresses acting on mining pillars, etc. Comparing the outputs of those models to threshold values, experts can conclude on the existence of a hazard (for instance if the height of caving is greater than the thickness of the overburden). They can also qualify a class of intensity for the hazard and zone it.

Modelling basically requires geometrical and mechanical data about the mining environment and the geological materials. In the context of the elaboration of MRPP, those data are sometime unknown and contain most of the time a significant part of uncertainty: the parameters are assessed from maps or expert hypotheses, the natural variability is not taken into account, etc. However, using back-analysis, expert knowledge, etc, the assignment of ranges of variation may be possible for each of the parameters of the models. Once those intervals of confidence are defined, methods as the Monte Carlo simulations may be used to express the uncertainty existing on the output of the model (Cauvin et al., 2005). Those methods allow experts to identify the parameters which have the greatest impact on the final result. They also allow to assess the probability that a certain variable (height of caving, stress acting on a pillar, safety factor of a slope) exceeds a certain threshold value (overburden thickness, pillar strength, security value (1.2; 1.5; 2; 3) respectively).

Concerning the spatial probability of occurrence of the hazard. Following the previous results, the spatial probability of occurrence of a hazard may be introduced. It may be defined as the probability that two different events occur at the same time: a source of hazard exists at a given location (event E) *AND* an analysis leads to the conclusion, given the quality of the modelling, that this source of hazard can have consequences on people safety, on infrastructures or on ecosystems located in its vicinity (event A). The probability, denoted as P(OSp) and written in (1), is strongly dependant to the model that has been used in the analysis. Therefore, it corresponds more to the assessed hazard than to the real hazard. As the 'time' parameter generally lacks in the geotechnical models, P(OSp) may be seen as the percentage of chances that a given site will be affected one day by a hazard.

$$P(OSp) = Prob(A \cap E) = Prob(E) \times Prob(A/E) \qquad (1)$$

In order to evaluate the probability of occurrence of a hazard, Didier (1999) combined two qualitative parameters. The meaning of those parameters seem to be very close to the ones introduced in (1). However, combining them *in a qualitative way* can add some confusion to the study. For example, two situations corresponding to very different conditions may coexist in a same class of 'probability of occurrence'. Therefore the understanding and the interpretation of the result of a risk analysis can become rather difficult.

Concerning the regulatory zoning plan. As indicated before, MRPP have to contain a regulatory zoning plan defining prohibitions, instructions or recommendations concerning land use, for both existing and future projects, as well as measures of prevention, monitoring and mitigation to adopt in risk areas. Some of the tools introduced in this study can be useful in the elaboration of these regulatory plans.

The mapping of the index of existence allows to identify areas where doubts exist regarding the real existence of a potential source of hazard. In those areas, investigations have to be undertaken in order to confirm the existence of mining workings. Regulatory plans are precisely aimed at defining such works that may be very important in a context of future land use management.

The use of Monte Carlo simulations in order to assess the level of a hazard may allow to identify the parameters whose uncertainties have the greatest impact on the risk evaluation. Once those parameters are identified, experts can prescribe recommendations aiming at improving the knowledge about the most critical parameters. That will directly induce a better accuracy of the hazard posting.

Example

In this part, a fictitious example of an old mining site will be used in order to illustrate the different advantages of the tools that have been introduced. The mining map of this area is presented in Figure 2, left.

The mining site can be divided into 4 different areas. Pillars in zone 1 are mentioned as "extracted" but doubts exist regarding the quality of the pillar extraction that occurred long time ago. Zones 2 and 3 have been exploited by a room-and-pillar extraction method. Pillars in zone 2 are smaller than in zone 3. However even though the extraction seems to be partial, the rooms might have been filled in or collapsed. Zone 4, also exploited by a room-and-pillar extraction method, is accessible and has been visited. Although several disorders may be expected on the surface above these 4 zones, this study will only consider the *sinkhole* hazard. Table 2 introduces values for the indexes of existence assessed using Table 1 and Figure 2 (right) maps them.

The analytical model developed by INERIS (Didier and Salmon, 2004) can be used to assess whether sinkholes may reach the surface or not. In this study, the overburden thickness is assumed to be constant for the whole area and equal to 40m.

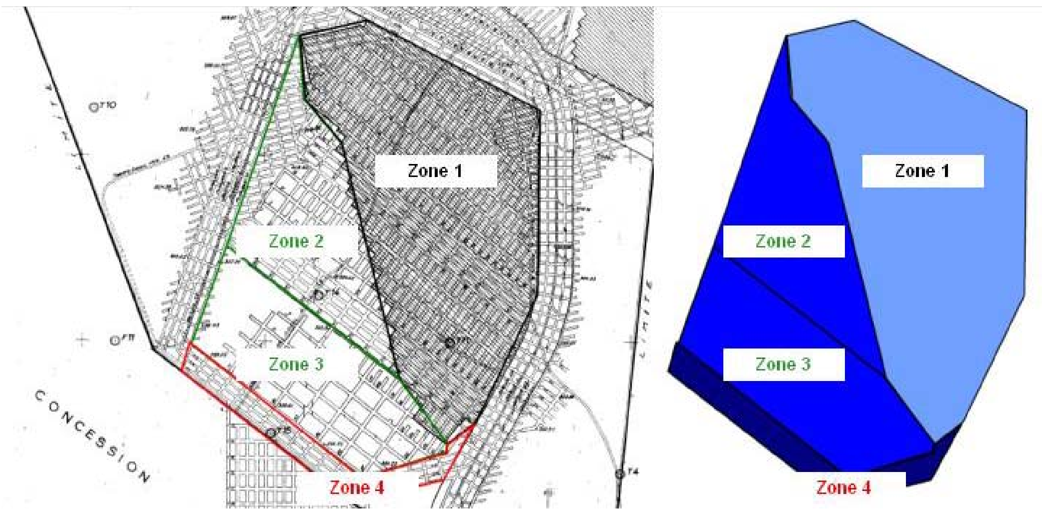

Figure 2. Mining site.

Table 2. Quality of the mining information related to the past mining workings.

Zone	Description	Source of information	Main problems	Index of existence
Zone 1	Pillars mentioned as “extracted”	Old mining map, low reliability	Some voids may exist underground	**3** (60 %)
Zone 2	Presence of room-and-pillars	Old mining map, low reliability	Galleries might have been filled in ; Pillars might have collapsed or might have been extracted	**5** (95 %)
Zone 3	Presence of room-and-pillars			
Zone 4	Presence of room-and-pillars	Direct visit on site		**5** (100%)

In this example, the parameters having a strong influence in terms of risk evaluation are the seam height (h) and the width of the room (w). Uncertainties exist on those parameters as they are determined from expert hypotheses or mining maps. Ranges of variation can however be defined for those parameters and Monte Carlo simulations can be performed to assess the height of caving. Table 3 introduces for each zone the probability, denoted P(A), that the computed height of caving exceeds the overburden thickness. If we only consider the computed deterministic heights of caving, zone 3 seems to be the only zone at risk. Even though the 37.5m-computed value is smaller than 40m, the 5 first meters of overburden are usually considered as very weak layers that can not bridge over the caving arch. For the other zones, the caving should not reach the surface. However, if we take into account the uncertainties of the input parameters, it appears that numerous simulations (up to 48% for zone 1) lead to a height of caving greater than 40m.

Using Tables 2 and 3, the hazard due to sinkholes may be characterized for each of the 4 zones. The intensity of the phenomena is the same wherever in the mining site as the diameter of the feared sinkholes is expected to reach 10m maximum. Probabilities of spatial occurrence of the hazard, P(OSp), can be assessed for each zone by using Eq.1 (Table 3).

In zone 3, we are almost certain that some underground voids exist and the computed height of caving is very close to the thickness of the overburden. This zone is the most critical of the whole mining site and precisions should be brought about the factors existing on surface. This induces the necessity of a complete campaign of investigations. The regulatory plan should then define surveying or risk mitigating measures, or even a total prohibition from building new infrastructures.

A difference exists between the spatial probability of occurrence of hazard in zones 2 (13%) and 3 (35%) although the quality of the mining maps is the same. It can be explained by the fact that as the rooms are narrower in zone 2, their self-filling requires less material than in zone 3. The “likelihood” that a sinkhole reaches the surface is thus smaller in zone 2 than in zone 3. The situations are also very different in zones 1 and 3 even though the values of the spatial probabilities of occurrence of hazard are very close. In zone 1, the problem mainly relies on the existence of underground voids and investigations have to be carried out near the surface stakes. If the researches performed to prove their existence are unsuccessful, the existence of risk due to mining might disappear.

Table 3. Hazard assessment.

	Description	Determination of the dimensions of voids:	Height (m) h	+/-	Width (m) w	+/-	Height of caving	P(A) %	Prob(OSp)
Zone 1	Pillars mentioned as "extracted"	Expert	3.5	0.5	4	10*	33.5 m	48	**29**
Zone 2	Presence of room-and-pillars	Use of mining map	3.5	0.5	4	1	33.5 m	14	**13**
Zone 3	Presence of room-and-pillars	Use of mining map	3.5	0.5	5	1	37.5 m	37	**35**
Zone 4	Presence of room-and-pillars	Known, in-situ measures	3.5		4		33.5 m	0	**0**

NB : The computing has been made using a radius of the sinkhole chimney of 5m, a bulking factor of the materials of 1.3 and a natural angle of break of 40°. *: The width of the voids in zone 1 has been assumed to range between the width of one single room and the width of the group of {room+pillar(6m)+room} corresponding to the total span in case of a pillar failure.

Conclusions

Two tools have been introduced in this paper: the index of existence and the spatial probability of occurrence of a hazard. These may have a great importance in the context of risk analysis. Used separately, they are able to identify and highlight the major problems experts have to face during the drawing up of risk analyses. They may also bring a better formalism concerning the integration of uncertainties into MRPP. Used together, they allow a better characterization of the hazard in quantitative way. However, the *real* probability of occurrence of a hazard can not be assessed exactly yet. It can only be evaluated given the quality of modelling. Research has now to be undertaken in this direction.

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