Development of post-mining multi-hazard assessment methodology

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ABSTRACT: Mining, natural and technological hazards can occur in a former mining site. The multi-hazard analysis becomes critical. This paper aims to establish the methodological basis for assessing the interactions between the main hazards identified in abandoned mines. The interactions between 57 hazards are analysed based on: theoretical aspects, feedback analysis and expert opinions. Interaction matrices and loops are used, helping to study the interactions between hazards.

Keywords: abandoned mine, multi-hazard, interaction, matrix, loop.

1 INTRODUCTION, OBJECTIVE AND METHODOLOGY

The number of abandoned mines is continuously increasing in the world. Several hazards can affect former mining sites (ISRM, 2007). Generally, several square kilometres of a mine site may be vulnerable to various types of hazards, including mining hazards, which may interact with each other. Multi-hazard assessment is mandatory in this case. Multi-hazard is frequently used to describe such a situation (Gill & Malamud, 2016).

This paper aims to present a first reflection to develop a methodology for abandoned mines which allows, in the long term, the identification and evaluation of the potential interactions between hazards. First, the methodology identifies residual mining, natural, and technological hazards. Then, three types of interactions were sought: mining hazards versus mining hazards, mining hazards versus natural hazards and mining hazards versus technological hazards. Interaction matrices and loops have made it possible to facilitate the analysis and visualisation of potential interactions. The potential retained interactions are the result of the following:

- the theoretical basis of phenomena,
- back analysis of the real-life case studies and,
- the feedback of the experts.

Three levels of interaction have been considered: no interaction or zero interaction potential; unlikely interaction(s) or low interaction potential and likely interaction(s) or high interaction potential.

2 DESCRIPTION AND ASSESSMENT OF HAZARDS

The hazards that may occur in a former mining site are grouped into three main categories: 19 mining hazards, 21 natural hazards and 17 technological hazards; see Table 3. For mining hazards, hazard qualification relies on predisposing factors. However, natural and technological hazard qualifications are based on the probability of occurrence or the severity of a hazardous event, meaning that a qualitative, semi-quantitative, or purely quantitative approach is sufficient for their qualification.

2.1 Mining hazards

The methodological guide for assessing mining hazards established by Ineris (Ineris, 2017) provides details on mining hazards listed in Table 3. Mining hazards can have several origins: ground movement hazards, self-heating hazards (only coal mines), hydrological and hydrogeological hazards, and gas release hazards. Induced seismicity, under certain conditions, after the cessation of mining operations also is considered in this article. However, this analysis does not consider the pollution hazard from an abandoned mine. A single mining hazard qualification depends on its intensity and the predisposition of the studied mine site. This assessment includes three intensity classes (*limited*, *moderate*, and *high*) and three predisposition classes (*very insensitive*, *sensitive* and *very sensitive*). Table 1 provides an example of the cross-referencing of predisposition and intensity, which results in assessing the mining hazard defined in three levels: low, moderate and high.

Table 1. Example of mining hazard assessment by cross-referencing predisposition and intensity for mining hazard assessment (Ineris, 2017).

Intensity	Predisposition		
	Very insensitive	*Sensitive*	*Very sensitive*
Limited	Low	Low	Medium
Moderate	Low	Medium	High
High	Medium	High	High

2.2 Natural hazards

Natural phenomena are increasingly well-known, studied and mapped at all territorial scales (Table 3). These natural hazards represent two groups: land-related and climate-related. Most atmospheric hazards are not considered in the remainder of this methodology as they have little or no interaction with mining hazards. Given the diversity of procedures available for natural hazard evaluation, this section presents a single evaluation method for flood hazard assessment. Indeed, the natural flood hazard of an area corresponds to its slow or rapid submergence when it is usually out of water. The hazard qualification corresponds to four levels: *low*, *moderate*, *high*, and *very high*, according to the water height and the dynamics linked to the combination of the water flow speed and the water rise speed (see Table 2).

Table 2. Qualification of the flood hazard according to the height and speed of the water.

Intensity	Water level	Dynamics		
		Slow dynamics	*Medium dynamics*	*Fast dynamics*
Limited	$H < 0.50\ m$	Low	Moderate	High
Moderate	$0.50 < H < 1\ m$	Moderate	Moderate	High
High	$1\ m < H < 2\ m$	High	High	Very high
Very high	$H > 2\ m$	Very high	Very high	Very high

Table 3. Summary of the mining, natural and technological hazards used in this multi-hazard analysis.

Mining hazards (19)	Code	Natural hazards (21)	Code	Technological hazards (17)	Code
Subsidence or progressive subsidence	SUB	Settlement	AFF	Gas explosions	EXP
Brittle subsidence	AFC	Localised collapse (sinkhole)	FON	Slick fire (liquid)	FEN
Crevasse	CRE	Dissolution (e.g., gypsum, chalk or salt)	DIS	Flare fire (gas or liquid)	FET
Localised collapse (sinking)	FON	Clay shrinkage or settlement	GON	Solid fire (combustible solids)	FES
Generalised collapse	EFG	Deep landslide	GSP	Boil over (heavy hydrocarbons)	BLO
Settlement linked to mining works	TAS	Shallow landslide	GSS	BLEVE (flammable liquefied gases)	BLV
Deep landslide	GSP	Gullying, reptation (erosion)	RAV	Liquid product release with vaporisation	RPL
Shallow landslide	GSS	Coastal erosion	ERC	Gaseous product release	RPG
Gullying, reptation or erosion	RAV	Mudflow	COU	Release of a liquefied gas	RGL
Mudflow	COU	Slump	EBO	Fire with the decomposition of toxic products	IPT
Slump	EBO	Rock or block fall	CHT	Release of radioactive substances	RSR
Rock or block fall	CHT	Avalanche	AVA	Discharge of water bodies	RME
Heating of veins or slag heaps	COM	Earthquake	SIS	Land movement due to human activities	MVT
Mine gas	GAZ	Volcanic eruption	ERP	Tank burst (Pneumatic energy release)	EBC
Modification of the groundwater discharge regime	IME	Forest fire	FEU	VCE (Combustion of gases, vapours)	VCE
Modification of the regime of a river	IMC	Settlement, consolidation	TAS	BLEVE (explosive vaporisation)	BLV
Flooding of topographic low points	IPB	Lowland flooding, as opposed to torrential flooding	INO	An explosion of solids (ammonium nitrate, pyrotechnics	ENA
Flash flooding - submergence	IBE	Flooding by runoff and mudslides			
Induced seismicity in former mines	SIS	Flooding by rising groundwater			
		Flooding by marine submersion			
		Heavy precipitation	PRE		
		Cyclone	CYC		
		Hurricane	OUR		
		Storm	TEM		

2.3 Technological hazards

Technological hazards result from permanent, intense or repetitive human activity around the abandoned mine site. They correspond to thermal effects, toxic effects, overpressure effects, and structure-related hazards (failure of civil engineering structures). Four classes help to define the intensity of the technological hazards: *indirect*, *moderate*, *severe* and *very severe* (Table 4). The probability of occurrence of an event (phenomenon), industrial installations are classified into five classes (French ministerial decree of 09/29/2005) from E (a possible but improbable event) to A (regular event).

Table 4. Technological hazard assessment

Intensity	Very severe			
Probability of occurrence	*> D*		*5E to D*	*< 5E*
Hazard level	*Very strong +*		*Very Strong*	*Strong +*
Intensity	*Severe*			
Probability of occurrence	*> D*		*5E to D*	*< 5E*
Hazard level	*Strong +*		*Strong*	*Medium+.*
Intensity	*Moderate*			*Indirect*
Probability of occurrence	*> D*	*5E to D*	*< 5E*	*All (A, B, C)*
Hazard level	*Medium+.*	*Medium*	*Low*	*Low*

3 IDENTIFICATION AND ASSESSMENT OF PHYSICAL INTERACTIONS BETWEEN HAZARDS

No methodological framework for multi-hazard analysis is dedicated exclusively to post-mining (Touili, 2018). Nevertheless, several methodological tools are available to study the interactions between natural hazards: the interaction matrix, the interaction loop, fault trees, multi-criteria analysis, and statistical vulnerability modelling, including temporal variability. The tools presented in this article are the interaction matrix and the interaction loop. The hazard interaction matrix displays the typology and potential of expert judgement interactions between source and target hazards. An interaction loop is a display tool which allows the typology and interactions between a source hazard, placed at the centre of the interaction loop and one or more target hazards which revolve around the source hazard.

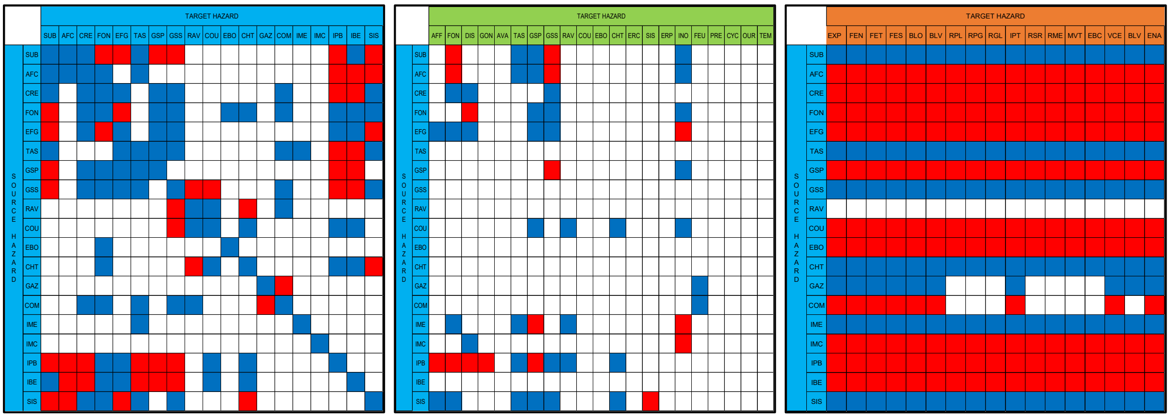
3.1 Hazard interaction matrix

The qualification of the hazard interaction is as follows:

- The interaction between two hazards has a *zero potential* (white colour also means no interaction) when they cannot interact at the same place due to the absence of common factors qualifying the two hazards or their associated mechanisms.
- The interaction between two hazards has a *low potential* (blue colour also means unlikely interaction) when the interaction is phenomenologically possible but not yet observed or when the changes caused are limited in scope.
- The interaction between two hazards has a *high potential* (red colour also means likely interaction) when the hazard interaction has already been in the same area or when the changes caused are very significant.

Figure 1 presents the hazard matrices based on the theory, feedback, and experts. The matrix of mining hazards is 19x19, which can potentially allow 342 interactions; however, at this stage of the study, only 128 interactions are possible (blue and red), corresponding to 37%. Forty-eight interactions present a high potential occurrence (red), corresponding to 14%. The matrix of mining-natural hazards is 19x21, which can potentially allow 399 hazard interactions. However, only 54 hazard interactions (blue and red) are possible, corresponding to 14%. Fifteen interactions present a high potential occurrence (red), corresponding to 4%. The matrix of mining-technological hazards is 19x17, potentially allowing 323 (19x17) interactions. Two hundred ninety-one interactions are possible (blue and red), corresponding to 90%. One hundred seventy-nine interactions present a high potential occurrence (red), corresponding to 55%.

Analysis of these matrices shows that interaction between source mine and natural hazards is less frequent than between mining hazards alone and that mining hazards interact mainly with flood hazards, whether mining or natural. The mine hazard can heavily impact technological hazards.



Mining-mining hazards *Mining-natural hazards* *Mining-technological hazards*

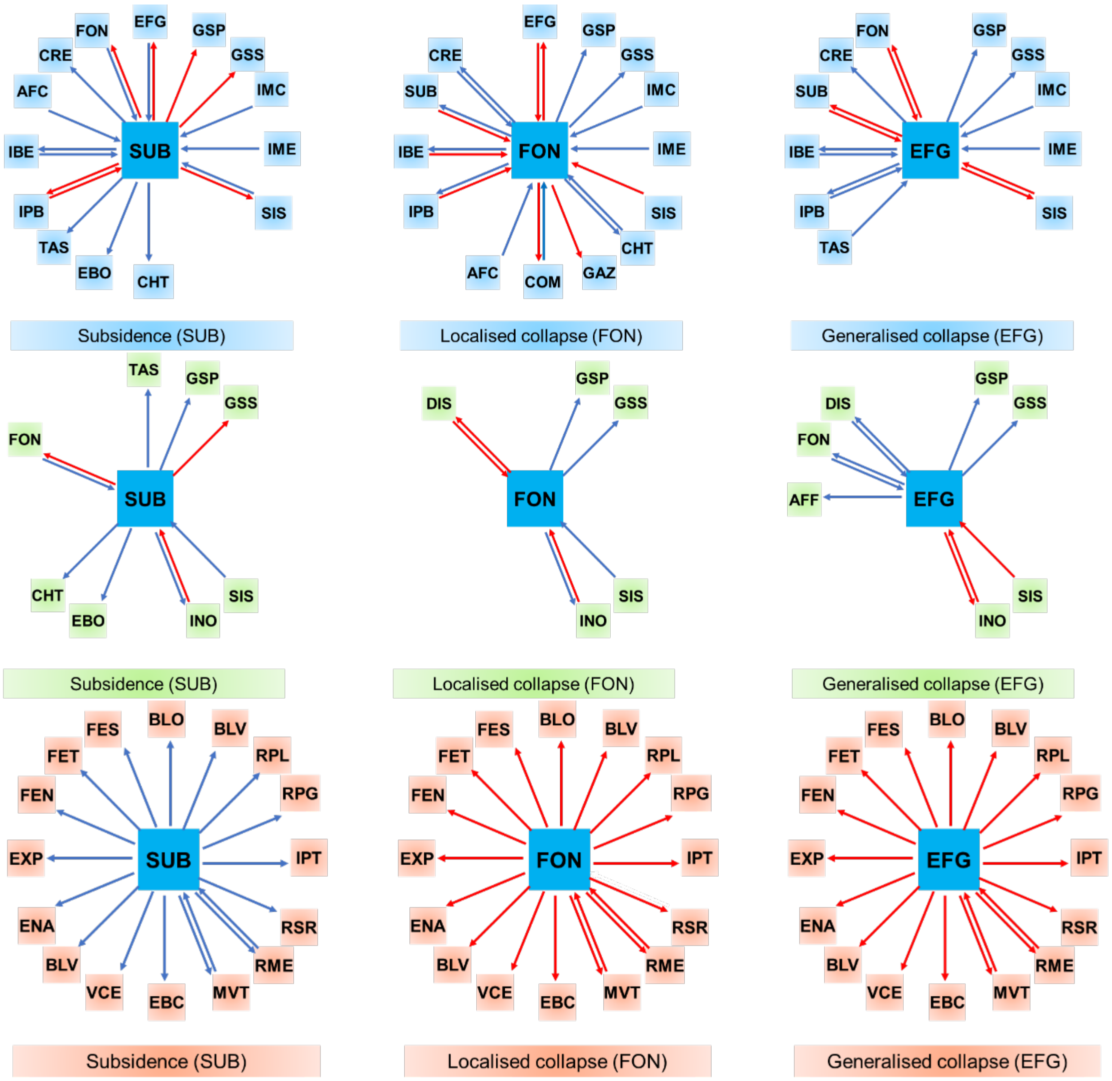
Figure 1. Hazard matrices based on the theory, feedback, and experts (red case: high potential interaction, blue case: low potential interaction, white case: no interaction).

3.2 *Hazard interaction loops*

The construction of the loops considers the source hazard at the centre of an interaction loop. The arrow from the loop centre to the target hazard can be split in the opposite direction, allowing a single or double direct interaction. The arrow colour represents the potential of the interaction. This mode of presentation, complementary to the interaction matrix, deals with one source hazard at a time; for example, Figure 2 presents interaction loops between a subsidence (SUB), a sinkhole (FON) and a generalised collapse (EFG) and the other hand mining, natural and technological hazards. For instance, subsidence can interact with eleven mining hazards, and eight mining hazards can interact with subsidence. Another example is the localised collapse mining hazard which can interact with all seventeen technological hazards. However, only two technological hazards can interact with the localised collapse mining hazard.

4 CONCLUSION

This paper proposes a methodological and representation basis for assessing interactions between hazards identified around former mines. After recalling the advantages of this multi-hazard analysis, the methodology consisted of identifying these hazards, reflecting the methods of individual evaluation, analysing the predisposition factors to identify by expert opinion and evaluating the potential of the possible interactions, and finally validating this methodology on concrete cases. The interaction identification is based primarily on hazard knowledge (nature of the event, predisposition or probability of occurrence and intensity). The three categories of hazards do not have the same evaluation methods. Among the tools used to display the results of the interactions, the authors retained the matrices and the loops as two complementary representation tools. Testing the method on former mining sites concerned by these interactions will be necessary, allowing better consideration of the risk and thus better preservation of the general interests identified around the abandoned mines.



Subsidence (SUB)

Localised collapse (FON)

Generalised collapse (EFG)

Subsidence (SUB)

Localised collapse (FON)

Generalised collapse (EFG)

Subsidence (SUB)

Localised collapse (FON)

Generalised collapse (EFG)

Figure 2. Interaction loops between subsidence (SUB), localised collapse (FON) and generalised collapse (EFG) mining hazards (red arrow: high potential interaction, blue array: low potential interaction).

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