Post-Mining Risk Management and multi-hazard approaches, methodology and application

Marwan Al Heib[*1,] *Marie* Degas[1], *Amélie* Lecomte[1] and *Christian* Franck[1]

[1]Ineris, Sites et Territoires, Parc d'Alata, Verneuil-en-Halatte, France

Abstract. After intensively exploiting the mineral resources of its subsoil for several centuries, French mining sites have gradually closed. The "post-mining" of a site mine is concerned by many hazards which can occur such as: ground movement phenomena (subsidence, collapses), rising gas, irreversible disruptions in underground water circulation induced by mining can potentially cause disturbances, both in terms of water circulation patterns (Flooding in low areas, disruption of waterway flows) and water quality (pollution). The multi-hazards assessment methodology consists of four steps: the identification and the assessment of the singles hazards, the identification of the potential hazard interactions, the identification of the level and the consequences of the interactions and the finally the adjustment and the mapping of the hazard interaction. The matrix tool and interaction organigrams are used to identify the potential interactions. The paper presents the methodology for the interaction between two main hazards: flooding and ground movement. The interaction methodology was applied on two case studies: shallow chalk mine and deep coal mine (France). The results demonstrate the importance of multi-hazard assessment. This analysis depends on the quality and the quantity of existing data for carrying out the multi-hazard assessment.

1 Introduction and objectives

In the mining context, the risk and hazard assessment studies have focused on a single hazard than multi-hazards [1-2]. However, closed mining areas are generally not affected by a single hazard, but two or more can act at the same time or consecutively [3-4]. Thus, assessing multiple hazards must be considered to improve the risk management. However, in a post-mining context, a multi-hazard assessment is not easily achievable because the available data for the different single hazards may refer to different spatial scales; comparisons, rankings and aggregations can be difficult; different specialised entities and experts need to collaborate. The paper focuses in two main hazards: ground movement and flooding [5]. The objective of this paper is to present the multi-hazard methodology developed in the POMHAZ project (European research project) to assess the interaction between two mining-natural hazards: ground movement and flooding. The paper will present first the

[1] Corresponding author: author@email.org

methodology used to assess one single hazard, the tools used to consider the interaction between hazards and finally the application on two case studies of shallow underground chalk mine and deep coal mine in France.

2 Multi-hazard assessment

The European Commission [6] considers multi-hazard analysis as the probability of occurrence [the probability of occurrence can be used to quantify a specific hazard) of different hazards, either occurring at the same time or shortly following each other, because they are dependent on each other or because they are caused by the same triggering event, such as rainfall, earthquake hazard or merely threatening the same elements at risk without chronological coincidence. The main reason of the development of multi-hazard approach is the reducing the cost of the hazards. The main advantages of multi-hazard of closed mines are: improvement of the quality of the risk assessment analysis, identification of the scenarios related to their interactions, better considering the vulnerabilities of a territory exposed to several hazards, improvement of the preservation of the general interests identified around closed mines and improvement in the resilience capacity and sustainability of the territories. However, multi-hazard risk assessment at local and regional scales remains a significant challenge due to the lack of data, causal factors, and interactions between different types of hazards [7]. Multirisk assessment tools can support decision-makers and provide them with information on mitigation measures [8].

2.2 Hazard interaction identification and methodology

To assess and presents the hazard interactions, different tools are generally used [9]. Among them: the hazard matrix, fault trees [10]; multi-criteria analysis [11-13]; the negotiated choice; the implementation of a multi-scale GIS (Global Information System) and statistical modelling of vulnerability including temporal variability [14] are used to assess the multi-hazards. Additionally, the experts opinion and feedback are generally used to assess the interaction between hazards (Figure 1). The interaction matrix presents the interrelation between n hazards (Hi to Hn), for instance, the source hazard (Hi) cand trigged several hazards (H, i to n). Figure 1 presents an interaction matrix for five hazards with the green colour means the interaction level is very low and limited, the orange colour means that interaction level is moderate and red colour is very important and has consequences in term of risk assessment.

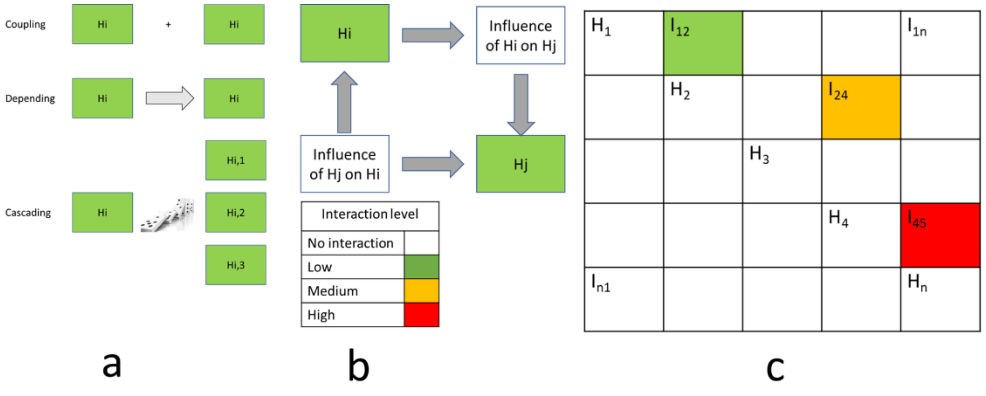

Fig. 1. Interaction matrix construction (a: interaction type, interaction loop, and interaction matrix) for assessing the potential hazards interaction [2].

3 Multi-hazard of mining context

3.1 Hazards categories

The main hazards related to post-mining are grouped into 3 prominent families for which the assessment methods are different: mining hazards (M), natural hazards (N) and technological hazards (T).

Table 1. Summary of the mining, natural and technological hazards used in this multi-hazard analysis.

Mining hazards (6)	Code	Natural hazards (6)	Code	Technology hazards (3)	Code
Subsidence	**SUB**	Subsidence	**SUB**	Suppression of water	**SURP**
Sinkhole	**SIN**	Sinkhole	**SIN**	Subsidence due to human activities	**SUB**
Massive mine collapse	**MMC**	Dissolution	**DIS**		
Settlement	**SET**	Clay settlement	**SET**		
Induced seismicity	**INS**	Natural seismicity	**NSI**	Flooding	**FLO**
Flooding	**FLO**	Flooding	**FLO**		

3.2 Mining hazard classification

The assessment of hazards in mining context is based on the history of the mining activities and the predisposition of the mining site instead of the probability of occurrence of the hazards or physical phenomena. In France, to assess a single mining hazard two stages are carried out:

• the first step is called "informative" stage, which consists 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.

• the second step is called hazard evaluation stage which defines the intensity and predisposition criteria described below and the severity level of the hazard.

Table 2. Mining hazard qualification

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

3.3 Mining hazards interactions

The methodology of the multi-hazard assessment is divided into four main steps (Figure 2):

The first step describes the three significant hazards families: mining, natural, and technological. The multi-hazard interaction follows the single hazard identification described in the section 3.2.

The second step of the analysis is the identification of the potential interaction based on the common factors of the hazards and conditions of the occurrences of the hazards. Possible interactions between hazards are based on the following: their nature (triggering or aggravating), their category (physical or regulatory), and their typology (dependent or independent).

The third important step is the description of the interactions. At this stage we should identify if the interaction is triggering, aggravating, and cascading (domino). Additionally, the interaction of hazards can have a regulatory impact. However, this paper is limited to the identification of the physical interaction description. In this step, the level of interactions between hazards should be assessed. The level of the interaction is based on the intensity of the single hazards and the level of the interaction. of the potential interaction using matrix interaction tool and/or the diagram tool.

The final (fourth) step concerns the visualisation (mapping) of the interaction of the hazards. Specific indicators can be used for the visualisation of the level and the type of the interaction.

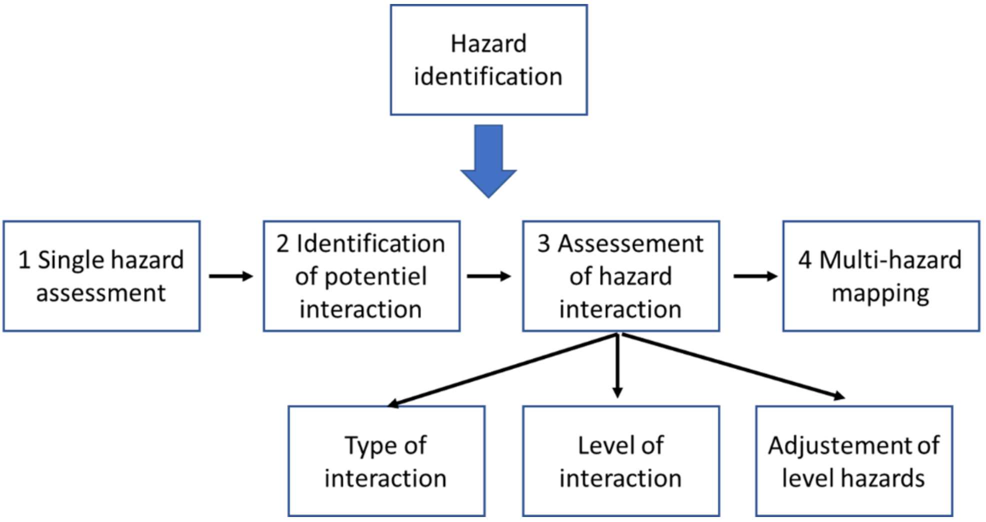

Fig. 2. Main steps of the multi-hazard assessment methodology from a single hazard to multi-hazards.

The assessment of the hazard interaction (step 3) can be carried out asking the following questions by the experts in charge of study to decide the type, the level, and the adjustment of the hazard interaction [2]:

Interaction conditions: are there specific conditions to be fulfilled? What are these conditions? How to evaluate their likelihood? Or is the interaction systematic?

Intensity: to what extent should a specific source phenomenon modify the target phenomenon intensity? What are the parameters that explain target phenomenon intensity?

Probability of occurrence: which parameters should modify the target probability of occurrence of the phenomenon?

Temporality: will the source and target phenomena coincide, or is there a buffer time between their occurrences? What are the parameters influencing the buffer time?

The third step also should identify the scales of the interaction between mining, natural and technology hazards: spatial scale and temporal scale. The spatial scale interaction can cover very limited surface (very local) to large surface (regional land). The temporal scale covers very short event, hours, to very long period (years). Certain ground movement mining hazards are very local and very short (e.g.: a sinkhole hazard). In the other hand, the flooding can be very local (flooding due to the failure of water supply network) or regional (heavy raining). In the other hand, certain hazard can concern a large surface (hectares) and can last a long time (years): self-fire or self-combustion of coal dump. Under specific condition, long drought period, the coal can start the self-heating. Thus, the self-heating hazard can trigger a pollution of water and air for a long distance, etc. In this example, it is very important to assess, not only the potential of the interaction, but also the scales of the interaction (spatial and temporal).

Additionally, this step concerns the adjustment of the initial hazard level. After the identification and the description of the hazard interaction, an adjustment of the level of hazards is mandatory. Line et al. propose to adjust the level of the initial natural hazard based on the level of the interaction. Based on this statement, we adopted the same method for the mining-mining hazard interaction and mining-natural hazard interaction. Table 3 presents the initial hazard level and the adjusted hazard. Three level of interaction are considered (low, medium, and high).

Table 3. Example of adjusted hazard level considering the multi-hazard analysis: hazard interaction.

<table>
<tr><th>Initial hazard level</th><th>Interaction level</th><th>Adjusted hazard level</th></tr>
<tr><td>Low / Medium / High</td><td>Low / No interaction</td><td>Low / Medium / High</td></tr>
<tr><td>Low</td><td rowspan="3">Medium</td><td>Medium</td></tr>
<tr><td>Medium</td><td>High</td></tr>
<tr><td>High</td><td>High</td></tr>
<tr><td>Low</td><td rowspan="3">High</td><td>Medium</td></tr>
<tr><td>Medium</td><td>High</td></tr>
<tr><td>High</td><td>Very High</td></tr>
</table>

3.4 Flooding - ground movement hazard interaction

The flooding hazard (FLO) can have natural, mining and technology origins. The ground movement can be subsidence, sinkhole, massive collapse, settlement, dissolution, and ground movement due to the naturel or induced seismicity. Figure 3 presents the flooding (FLO) interaction with ground movement hazards. We assessed the potential interactions based on the following arrangements:

- The flooding can decrease the strength of the rock mass and the discontinuities.
- The flooding can modify the initial and induce stress distribution.
- The ground movement can modify the topography of the land.
- The seismicity (natural and induced) modifies the initial equilibrium conditions.
- The external factors such as heavy lorries, the vibration, and the external earth work (such as excavation) trigger the flooding or/and the ground movement hazards.

The interaction organigram for the flooding – ground movement hazards is constructed. Based on the feedback and experts discussion that 15 potential interactions were identified, seven of them are considered as high-level interactions. For instance, the flooding can trigger and interact strongly with the occurrence of the sinkhole (SIN), the massive collapse (MMC), settlement (SET) and the dissolution (DIS). In the other hand, the ground movements (SIN, SET, DIS) can interact lowly with the flooding. Additional analysis and conclusions can be made based on the interaction organigram that can help to assess the interaction between several hazards. One can also noticed the possibility to build different hazards scenarios. For instance, the seismicity can induce flooding hazard and the flooding can induce the occurrence of a sinkhole of a shallow mines and cavities. The scale of the interaction in this case: seismicity is a regional and very short hazard, flooding is a regional or local, but can take days/weeks, and the sinkhole is very local and short hazard. Thus, the interaction between the hazards is possible if only they spatial and temporal conditions exist together.

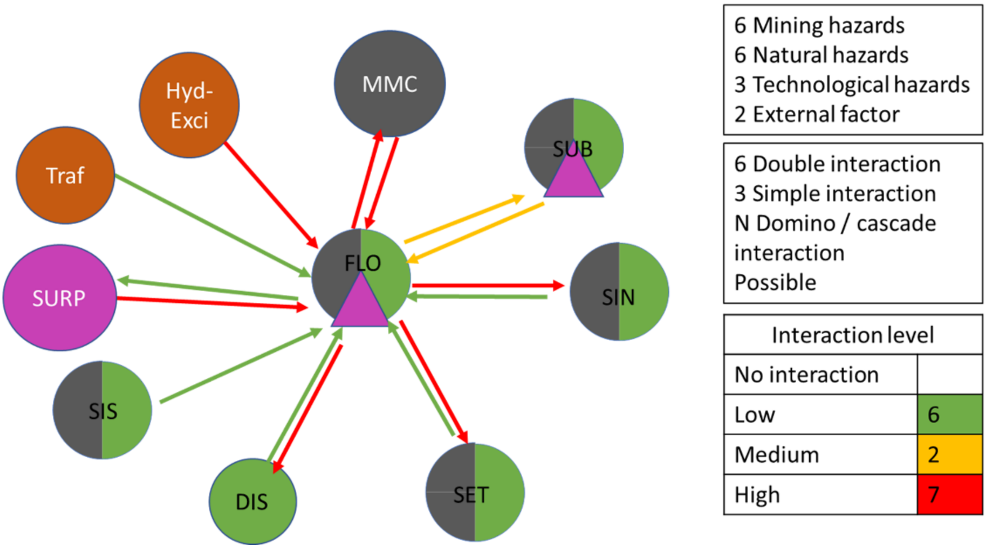

Fig 3. Interaction organigram between the flooding and the ground movement hazards, (mining-grey, natural-green, and technology-pink).

4 Application of the Methodology to a case study

The methodology presented previously will be applied on two case studies. The first case study concerns a chalk shallow mine and the second one concerns a closed deep coal mine.

4.1 Underground chalk mine

The first case study concerns an underground chalk mine located in the north of France. The underground has old stone underground. The underground mines are generally of small dimensions exploited by the method of rooms and pillars. The extraction ratio varies between 50 and 85%. Their depth varies between 6 and 30 m depending on the nature of the covering and the level of the water table. The height varies between 2 and 11 m, and the width varies between 2 and 5 m. The methodology described in the paper was applied (Figure 2). Based on the nature of the rock, chalk very soft rock, and the geometry of the underground mine (depth, extraction ratio), the main identified hazard is the ground movement associated with the collapse of underground mine. Additionally, several events were recently recorded related to the heavy rain or climatic events. The interaction between ground movement and the flooding is evident, this corresponds to the second step of the methodology. The third step corresponds to the assessment of the multi-hazard interaction. According to the available documents, the area is affected by flooding by rising groundwater (RWT) and flooding by runoff (ROF). Two types of analysis were carried out: global analysis and detailed analysis.

For the first analysis or global analysis, we grouped all flooding types in one hazard (FLO). Figure 4 shows the interaction between the two hazards, based on the geological, topographical, etc., conditions of the municipality. The trigger of the ground movement can be the result of the flooding or/and the effect of the heavy traffic (TRA) and the earth work and excavation (EXC). We have therefore considered that there is a strong interaction between flooding of natural origin (strong precipitation and rising water table) and ground movement (sinkhole and subsidence). The flooding results in a weakening of the overburden and of the mine structures (pillar and roof). In the other hand, the ground movement has low interaction level with the flooding. For the second analysis (Figure 3), we sought to identify the interaction between the GMVT hazard and three flooding hazards (sub-hazard). Only the number of the interactions with hazards are considered, 4 potential interactions were identified: flooding by rising water table (RWT), flooding by runoff (ROF) and flooding by overflowing of stream, canal, river (OFS). Tow external factors can play a role: the heavy traffic (TRA) and the earth work and excavation (EXC). It should be remembered that the latter is linked solely to the presence of the channel, a hazard can be considered low. We note that only the OFS hazard corresponds to a double interaction, the OFS interacts and has an impact on the GMVT and the GMVT in turn impacts the OFS hazard.

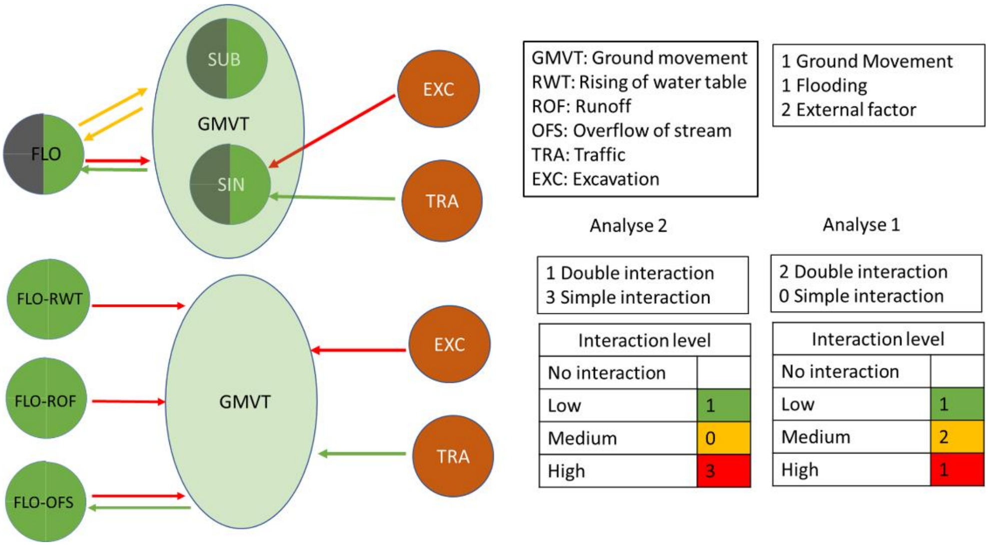

Fig. 4. Interaction of flooding (FLO) and ground movements hazard (mining-grey, natural-green) – chalk underground mine, *only the number of the interactions with hazards are considered.

4.2 Underground coal mine

The second case study concerns a deep coal mine (depth > 500 m) extracted using long-wall mining method. The mine is closed since more than 20 years. Near the surface, in addition to the deep coal mine, there is an abandoned underground shallow (depth < 100 m) limestone mine. We focused only in the third step of the methodology. We analysed the interaction between the identified ground movement hazards due to the coal mine, limestone mine, natural cavity, and flooding hazard. Table 4 presents the level of the hazards before considering their potential interactions.

Table 4. Coal mine -intensity level (low=green, moderate=orange, severe and very severe=red) of the mining hazards (4) and natural hazards (3).

Hazard		**Low**	**Medium**	**Severe**
Mine hazards (4)	Sinkhole (SIN)			
	Subsidence (SUB)			
	Landslide (LSG)			
	Settlement (SET)			
Natural hazards (3)	Sinkhole (SIN)			
	Settlement (SET)			
	Flooding (FLO)			

The organigram and the interaction matrix were built based on the assessment of the factor of each hazard (Table 5 and Figure 5). The organigram (Figure 5) is focused between the flooding and the ground movement hazards. This analysis demonstrated that the flooding hazard (FLO), due to the natural flooding (e.g., heavy rain) can trigger several mining hazards: subsidence (SUB), settlement (SET), landslide (LSG), and sinkhole (SIN). In addition, the flooding and the water fluctuation can increase the ground movement intensity or level, decrease the strength parameters, and mobilise the faults and discontinuity displacement. The interaction is high between the ground movement (sinkhole, subsidence, and settlement) with the flooding hazard is high. The interaction between the subsidence and the flooding is moderate. The Table 5 presents the matrix of interaction between mining and natural hazards (source hazards) and the mining hazards (trigger hazards). The blank case corresponds to the interaction of the hazard of itself. For instance, we noticed the interaction between subsidence and sinkhole is high. That means if a sinkhole is occurred in the sector, that can trigger the subsidence. Also, the sinkhole hazard can trigger the settlement and the landslide.

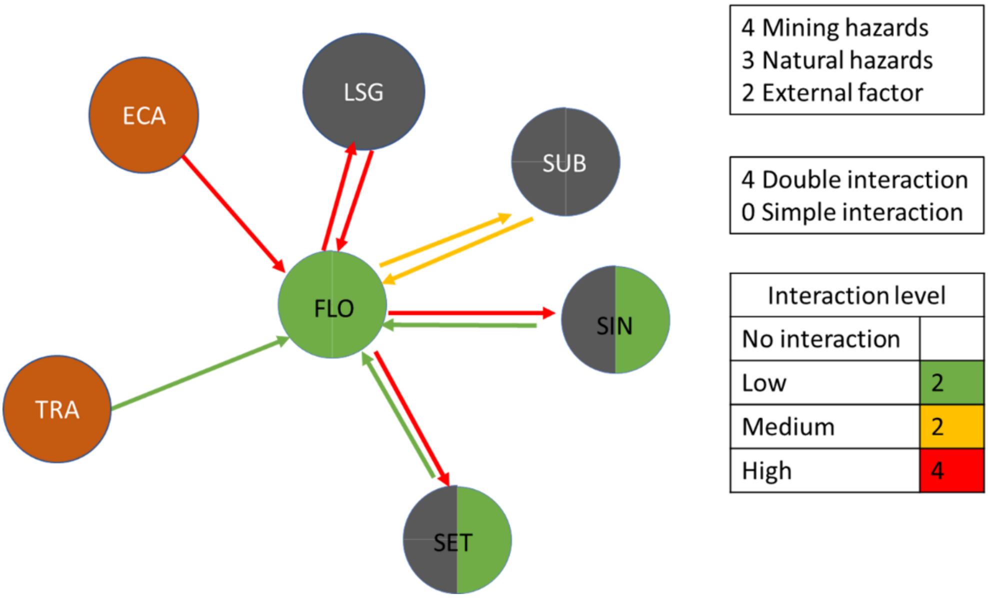

Fig. 5. Interaction of flooding (FLO) and ground movements hazard – coal underground mine – (mining-grey, natural-green), * Only the number of the interactions with hazards are considered.

Table 5. Multi-hazards interaction matrix and assessment of the level of the interaction: red high, yellow: medium, green: low.

Source hazards		Trigger hazards – mining hazards				
		Code	SIN	SUB	LSG	SET
Mining	Sinkhole	SIN				
	Subsidence	SUB				
	Landslide	LSG				
	Settlement	SET				
Natural hazards	Sinkhole	SIN				
	Settlement	SET				
	Flooding	FLO				

The matrix of the interactions and organigram highlighted the importance of the interaction between the hazards in one hand and the role of the flooding.

Based on the number of interactions (Table 5), we suggested the adjustment of the initial level of the 4 mining hazards (Table 6). We noticed that three mining should be adjusted. The sinkhole hazard passes from low level to severe because of the number of interactions. That means for the zones concerned by the sinkhole, we should be verified the existing of the other mining and natural hazards. For the subsidence hazard, the initial level passes from low to medium, and from medium to severe.

Table 6. Initial and adjusted mining hazard level based on the interaction level between mining hazards and the flooding hazard

Mining hazard	Interaction level	Initial hazard level	Adjusted hazard level	Initial hazard level	Adjusted hazard level
SIN	High	Low	Moderate	Moderate	Severe
SUB	Moderate	Low	Moderate	Moderate	Severe
LSG	High	Low	Moderate		
SET	High	Low	Moderate		

5 Conclusions

The paper discussed the application of the multi-hazard assessment in post-mining regions. The work presented in this paper concerns the application of multi-hazards methodology developed in the POMHAZ project and national research programs carried out by Ineris for assessing the risk of post-mining areas. The paper focused on the ground movement and flooding hazards. They can have different origins: natural, mining and technology. Two tools were used to identify the different potential interactions: matrix and organigram tools. Three level of interactions were identified low, moderate, and high. The initial level of ground movement and flooding hazard should be adjusted based on the level of the interaction. For both case studies analysed, the impact of the flooding hazard on the ground movement is high. The initial level of ground movement was adjusted based on the interaction level. More hazard interaction scenarios can be analysed and considered.

In conclusion, the multi-hazard assessment presents a real advantage for mining regions because can reduce the cost of the consequences of the hazard interactions. However, the policymakers and stakeholders should create a collage of experts capable to assess the interaction of hazards.

Acknowledgements: This work has received funding from the European Union's Research Fund for Coal and Steel (RFCS) under the European project "POMHAZ, https://www.pomhaz-rfcs.eu/" grant agreement No 101057326 and supported by the Ineris programs.

References

1. D.N. Parry, C.P. Chiverrell, *Abandoned mine workings manual*, C758D. Construction Industry Research and Information Association (London, UK, 2019)
2. M. Al Heib, C. Franck, H. Djizanne, M. Degas, Sustainability **15**, 8139 (2023)
3. A. Azhari, U. Ozbay, International Journal of Rock Mechanics and Mining Sciences, **100**, pp. 218-228 (2017)
4. A. Mavrommatis, D. Damigos, S. Mirasgedis, Infrastructures, **4**, 38; (2019)
5. P. Gombert, A. Cherkaoui, Tunnels and Underground Areas **240**: 468-482 (2013)
6. European Commission. *Risk Assessment and Mapping Guidelines for Disaster Management. Brussels*: European Commission, (2010)
7. N. Touili. ISTE Open Science, Published by ISTE Ltd. London, UK – openscience.fr (2018)
8. Komendantova, N. et al. International Journal of Disaster Risk Reduction, **8**: 50–67. (2014)
9. Z. Liu, F. Nadim, A. Garcia-Aristizabal, A. Mignan, K. Fleming, B.Q. Luna Georisk, **9:2**, 59-74 (2015)
10. L. Eshrati, A. Mahmoudzadeh, M. Taghvaei, International Journal of Health and Disaster Management, vol. **3**, Issue 2, pp. 79-88. (2015)
11. F.G. Sigtryggsdottir, J.TH. Snæbjornsson, L. Grande, Nat hazards, **79**:1299-1331 (2015)
12. M. Merad, T. Verdel, B. Roy, S. Kouniali, Tunneling and Underground Space Technology, 3, vol. **19**, no. 2, pp. (2004)
13. M. Mladineo, N. Mladineo, N. Jajac, Croatian Operat. Research Review, **5(2)**, pp.415-425 (2014).
14. F. Mancini, F. Stecchi, G. Gabbianelli, G. Engineering Geology, 11/20, vol. **109**, no. 3–4, pp. 170-182. (2009)
15. H. Djizanne, M. Al Heib, A. Gouzy, C. Franck, *Development of post-mining multi-hazard assessment methodology*. 15th ISRM Congress & 72nd Geomechanics Colloquium (Vienna, Austria, 2023).
16. R. Salmon, C. Franck, Th. Lombard, R. Hadadou. *Post-Mining Risk Management in France*. 2019, Ineris - DRS-19-178745-02406A. https://www.ineris.fr/fr/post-mining-risk-management-france.