Research Article Open Access

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The risk of collapse in abandoned mine sites: the issue of data uncertainty

DOI 10.1515/geo-2016-0022

Received September 04, 2015; accepted December 08, 2015

Abstract: Ground collapses over abandoned underground mines constitute a new environmental risk in the world. The high risk associated with subsurface voids, together with lack of knowledge of the geometric and geomechanical features of mining areas, makes abandoned underground mines one of the current challenges for countries with a long mining history. In this study, a stability analysis of Montevecchia marl mine is performed in order to validate a general approach that takes into account the poor local information and the variability of the input data. The collapse risk was evaluated through a numerical approach that, starting with some simplifying assumptions, is able to provide an overview of the collapse probability. The final results is an easy-accessible-transparent summary graph that shows the collapse probability. This approach may be useful for public administrators called upon to manage this environmental risk. The approach tries to simplify this complex problem in order to achieve a roughly risk assessment, but, since it relies on just a small amount of information, any final user should be aware that a comprehensive and detailed risk scenario can be generated only through more exhaustive investigations.

Keywords: risk analysis; numerical method; uncertainty; risk scenarios; roof collapse; mine heritage

1 Introduction

Historic underground mining activity has left us with a critical legacy all over the world. The risk associated with abandoned mines requires careful consideration because these dismissed mines can generate several forms of damage to the surrounding environment: collapse of large areas, subsidence, pollution, etc. As reported by several authors [1–5], abandoned mines have serious implications for the land: a number of authors have studied the impact of mines on surface stability [6–17], while others have focused on pollution of the environment [18–24].

Abandoned mines are now considered a new environmental risk [25] and, as a consequence, in some countries mine closure requires long-term risk assessment, as well as preparation of closure plans aimed at protecting public health and mitigating environmental damage to the surrounding areas [13, 26, 27]. Although a census has identified more than 2400 abandoned mines in Italy [28], law does not currently promote any form of long-term management of mine sites, and guidelines for mine rehabilitation have not yet been defined. Abandoned mines therefore represent a continuing threat to public health in Italy because the closure of these sites will increase the risk of collapse or pollution of the surrounding area. As for many other geo-engineering issues, lack of knowledge and uncertainty are crucial points in problem-solving [29]. In abandoned mines, uncertainty can be related to both the intrinsic heterogeneity of the geological features, and the lack of detailed knowledge of voids in terms of tunnel section, depth of the tunnels, the number of exploitation levels, and so on. This problem is still more critical because no funding is generally allocated to investigate these areas, due to the absence of economic interest once the mine site has been abandoned. Additionally, in some cases direct investigation cannot be performed inside mines due to stability problems or to the presence of water.

Because of unavailable or inaccurate information with respect to other natural risks [30–33] assessment of dismissed mines demands for approaches based on simplifying assumptions for the quantification of risk [34].

In this work, we propose a methodological approach to evaluate the risk of collapse of abandoned mine sites, addressing the issues related to data unavailability and data uncertainty. The final goal is to provide decision makers with useful tools [35] capable to set action priorities minimizing the use of public funds.

We focus on a case-study of an underground mine in Northern Italy that was abandoned in 1958 after a massive collapse involving all mining levels. The inaccessibility of this site and the difficulty to obtain information makes this

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case a prototype test-bed for the definition of a general methodology for collapse risk scenario evaluation at abandoned mine sites. Section 2 briefly presents the case study and the proposed methodology. In Section 3 the different steps of the methodology are detailed explained thanks to their application to the case study. Section 4 discusses the results of the risk analysis through a "summary approach". Finally, a general conclusion is reported highlighting the importance to properly consider data uncertainty even if only a rough risk analysis may be achieved.

Though the proposed methodology is here applied to a specific site, it could be easily exported to other case-studies.

2 Materials and methods

2.1 Setting

The case-study is located in Montevecchia, a small historic village standing on the flanks of a 500 m-high isolated hill in Northern Italy. From a geological point of view, the area features Flysch facies, called Flysch di Bergamo, which consists primarily of a sequence of shale, marl and sandstone. A huge megabed, the Missaglia Megabed [36], is present in the flyschoid complex (Figure 1a). According to the literature [37, 38], the Megabed is considered a unique deposit produced by exceptional sedimentary processes such as debris flows and turbidity currents. The term Megabed is used for beds with great thickness and different composition from their host sequences. The Missaglia Megabed is 40 m thick and consists of megabreccia in the lower part (2-3 m of thickness) and a homogeneous segment of calcarenite-marl in the upper part. From a tectonic point of view, folds are the dominant structures in this area, with a sequence of anticline-syncline WNW-ESE trending folds. Figure 1b shows the geological section of the exploited Megabed, in which, as stated above, the Megabed is composed of a chaotic band, basal breccia, and a more homogenous calcarenite-marl unit.

Montevecchia mine (Figure 2a) was exploited from the late twenties for almost 3 decades to extract marl rock that was used to produce concrete. According to collected documents, the mining site could be roughly divided into three sections: the east section, where six tunnels were excavated, the central section, which had 7 levels and was the most heavily exploited (in terms of tunnel section), and the west section, which had still seven levels but with smaller size (Figure 2b). All levels develop eastwards from mine entrance, with a maximum length of 450 m and maximum depth of 100 m. The uppermost mine level is at an elevation of 430 a.s.l. and approximately 45 m below ground surface, and the levels were excavated with a planned distance (from base to base) of about 15 m. Nevertheless, a number of miners reported that several tunnels were enlarged (up to 20 m) and the distance between levels was reduced, regardless of the mine exploitation plans. These modifications were most likely performed to obtain greater economic advantages, to the detriment of mine safety.

Table 1 lists the most important events according to the collected historical documents. In 1956 the mine experienced first significant stability problems, with partial collapses of the roof of the lowest level, and, subsequently, between the third and the forth levels. Extraction activities continued but were limited to the first 3 shallower levels and just in the middle section of the mine. In 1958 a large sinkhole of approximately 10000 m2 occurred on top of the hill (Figure 3) because of a massive collapse involving all mining levels in the central part of the mine. Mining activity ceased, the site was abandoned, and the road running above the mine along the hill ridge had to be deviated and repaired; a parking lot that still exists was also created in the area previously affected by the sinkhole. A number of investigations were recently performed in order to evaluate the safety conditions of the mine and the possible risk of other events like the 1958 sinkhole [39]. Failures of the areas to the east and to the west of the previous collapse would directly concern human settlements.

2.2 Methodology

For a better understanding of the risk associated to the presence of abandoned mines, we propose a 3-step approach depicted in the flowchart in Figure 4 and described hereafter. The first step of the methodology concerns the characterization of the problem with the aim of defining a conceptual model of the abandoned mine as detailed as possible. The input data to this step include historical documents and miners' statements, which are mainly useful to understand the geometrical features of the underground voids, along with geomechanical parameters that are often obtained by means of direct investigations in the field.

The second step of the proposed methodology involves the simplification of the problem through the definition of a limited number of reference states or scenarios, according to which the outcomes of the last step of the procedure will be grouped.

The third and final step is risk assessment and it is achieved through a numerical approach. First of all a stability analysis is performed and then, due to the lack of

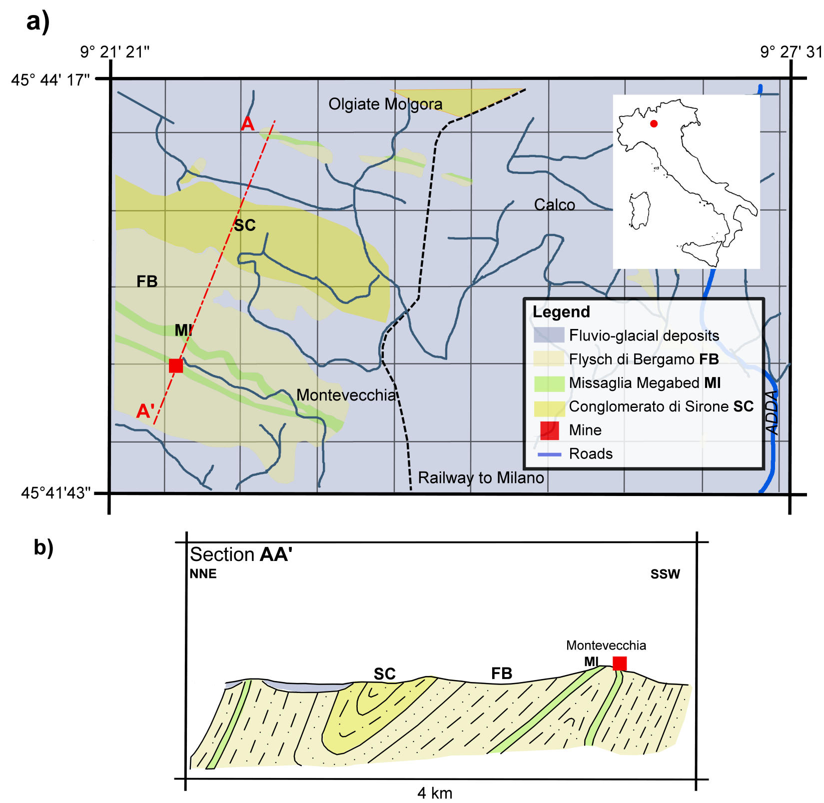

Figure 1: (a) Lithological sketch and (b) geological section of Montevecchia area (Modified after [64]).

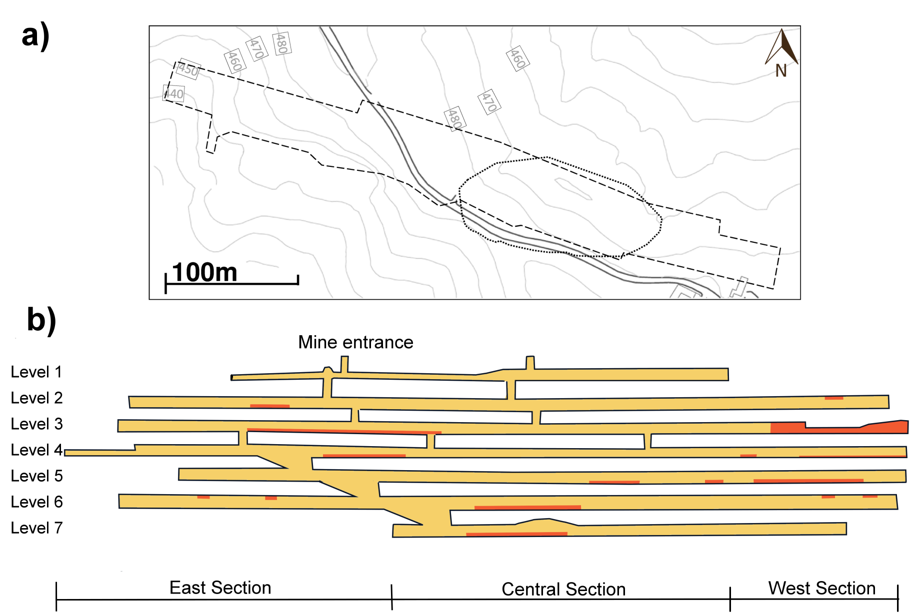

Figure 2: (a) Exploited area, dashed area is the contour of the mine footprint, dotted area delimits the 1958 sinkhole (b) Sketch of mine depicting the mining levels (not to scale); red areas indicate collapses reported during mining activity.

Figure 3: Pictures of the 1958 sinkhole.

Table 1: Historical documents.

Year	Main facts and events
1928	Opening of marl extraction activities.
1930	A technical report states that exploitation of Montevecchia mine cannot cause problems to natural springs.
1931	Only the first level is exploited with a the tunnel having a section of about 3-5 m.
1932-35	Exploitation of the first level is completed and new deeper levels with larger sections are excavated.
1936	Exploitation of the third level is completed.
1940	A technical report confirms two important springs has vanished most likely because of mine exploitation. The most important spring in the area vanishes at the end of the year.
1947	Exploitation of the 4th and 5th levels is completed. The distance between tunnels is about 15 m from base to base.
1954	Several tunnels are exploited with increasing section (7-8 m). There are 7 mining levels and overexploitation affected the central section of the mine.
1955	Miners report that some tunnels were enlarged (up to 20m) and the distance between levels was reduced, regardless of the mine exploitation plans
1956	First significant failures with partial collapses of the roof of the lowest level, and, subsequently, between the third and the forth levels. Activities are limited to extractions at the first 3 levels and just in the middle section of the mine.
1958	Extensive collapse of the mine at all levels and end of extraction activities.

knowledge coupled with the intrinsic uncertainty associated with abandoned mines, a sensitivity and uncertainty analysis are carried out. Starting from the idea of a simple approach, sensitivity and uncertainty analysis are performed around a reference case: the stability analysis reported in the Paragraph 3.3.1. Finally, a summary of all the possible outcomes are discussed in order to define the final collapse probability.

3 Results

3.1 Conceptual modelling

For our case-study, the analysis of mining claims, plans, cross sections and technical reports was particularly useful to determine the number of tunnels and their sections (see Paragraph 2.1). Instead, geological and geophysical investigations were carried out to characterize the features of the rock mass. Geological mapping was performed outside the mine across two outcrops in the Flysch facies and in the Megabed and results are listed in Table 2. A Schmidt hammer was also used to measure joint compressive strength (JCS) in Missaglia Megabed. Field data were analyzed in order to gather useful information for definition of the geomechanical properties of marl and flysch. Rock mass classification systems have been successfully applied to provide reliable input data for numerical approaches. Rock mass rating (RMR- [40]), Q-system (Q- [41]) and Geological Strength Index (GSI- [42]) are the main classification systems used in the mining industry. In this work these methods have been applied to both Flysch and Megabed outcrops (Table 3).

Though use of rock mass classification is a conventional procedure for defining the input data for numerical simulation, the outcome of a geophysical survey can be used to better estimate some geomechanical properties of the rock mass. Seismic is definitely the most interesting method among the geophysical techniques when the objective is assessment of the rock mass's mechanical properties. Three techniques that appeared to be promising for the case at hand were selected: refraction seismic, multichannel analysis of surface waves (MASW), and transillumination experiments (a sort of tomography with very limited angular coverage because of the restrictions on entering the mine). Thanks to the geophysical surveys rock layers with different properties in term of P- and S-waves were identified [39, 43], from which the rock's elastic parameters can be estimated.

3.2 Collapse options

For a rough risk assessment a simple classification of the numerical outcomes to facilitate the comparison of the results of several simulations is required. Therefore, an easy way to quantify the risk collapse is introduced by the use of some references states [44]. This is one important simplifying assumption in order to permit a final summary risk analysis that takes into account all the performed simulations. The proposed collapse options are: no collapse (stability), minor collapse in two tunnels at most with some movements of blocks (that means partial instability) and extensive collapse that involves all tunnels, like the event of 1958 (instability). The three risk reference levels are then coded as green, yellow and red. An example is reported in Figure 5.

3.3 Numerical modelling

The management of several natural disasters (landslides, floods, hurricanes and so on) is often based upon the hypothesis of different risk scenarios [45, 46], defined through use of the available information. Despite this, risk scenarios are valuable only if believable and rigorous from a scientific point of view [47–49].

For the case study, the available data do not permit to carry out a detailed analysis. Therefore, among many different approaches, a simplified numerical method fits the aim of the paper because capable of estimating a hint of the collapse risk with the current knowledge of the site. To accomplish this goal, numerical code was used in two steps: 1) the stability analysis; 2) the multiple scenario that takes into account the variability of the case-study considering a range of possible values of the input data in numerical analysis.

For what concerns the numerical code, jointed rock masses are usually simulated by the distinct element method [50] or by discontinuous deformation analysis [51] and among these, in the present work, the distinct element method 3DEC (a three-dimensional code developed by Itasca in 2008) was chosen to provide the stability analysis of this abandoned mine site.

3.3.1 Stability analysis

The first step deals with a simple stability analysis. This analysis is then considered as the reference case around which the uncertainty and sensitivity analysis are performed. A stability analysis with the lack of knowledge of

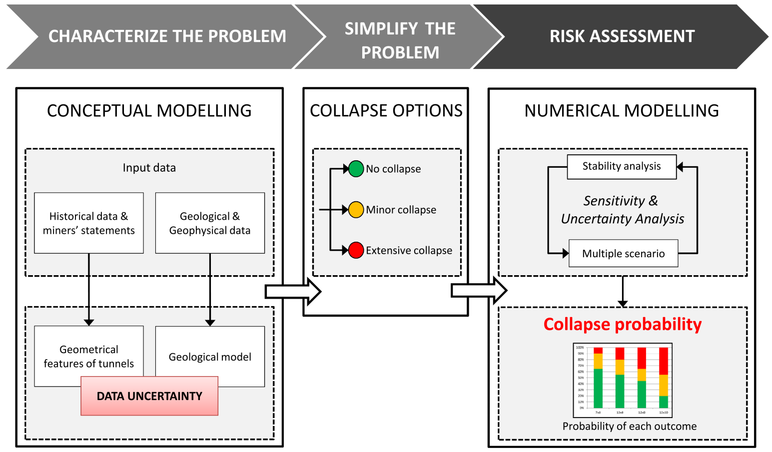

Figure 4: Flowchart of the methodology to define the collapse probability.

Table 2: Joint set features of Flysch facies and Calcarenite-Marl strata. K1 joint set has similar features in both the two lithotypes, while K2 joint set has different dips.

		FLYSCH DI BERGAMO			
Joint set	dip direction (°)	dip (°)	Persistence (%)	Spacing (m)	aperture (m)
	29	80	100	0.050-0.015	0
K1	123	86	80	0.5-1.0	0.001-0.003
K2	212	46	70	-	0.001-0.003
		MISSAGLIA MEGABED			
Joint set	dip direction (°)	dip (°)	Persistence (%)	Spacing (m)	aperture (m)
K1	123	86	85-90	1.5-2.0	0.02-0.05
K2	195-215	75-85	85-90	2.5-3.0	0.02-0.05
K3	0-10	0-5	85-90	2.0-2.5	0.02-0.05
		JCS 52 Mpa			

Table 3: Geomechanical classifications of rock mass.

Geomechanical classification	Flysch	Megabed
Q system	0.7	1.27
GSI	40-45	45-50
RMR (Q)	41	47
RMR (GSI)	45-50	50-55

Table 4: Input data for 3DEC model.

Numerical model geomechanical characterization			
Missaglia Megabed			
Property	Data source	Data	
Rock Density	Measured	2230	Kg/m3
Rock matrix Young modulus	Modulus ratio	31	GPa
Rock matrix Poisson's ratio	Hoek Brown law	0.28	
Joint normal stiffness	Literature	0.8	GPa/m
Joint shear stiffness	Literature	0.4	GPa/m
Joint set 1	Survey	123°/86°	
Joint set 2	Survey	205°/80°	
Joint set 3	Survey	Sub horizontal	
Flysch di Bergamo (GSI 40)			
Rock Density	Measured	2300	kg/m3
Rock matrix Young modulus	Modulus ratio	2.9	GPa
Rock matrix Poisson's ratio	Hoek Brown law	0.3	
Cohesion	Hoek Brown law	0.3	MPa
Tensile strength	Hoek Brown law	0.8	MPa

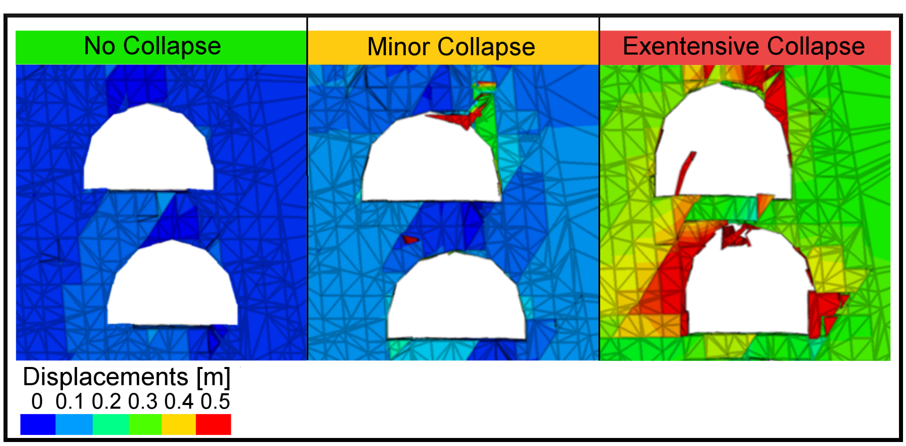

Figure 5: Examples of Prototypal cases to demonstrate the classification criteria: the first in green for stability assessment, the second in yellow for partial instability and the last in red for global instability.

the input data is not a straightforward procedure and, often does not lead to a unique outcome. It is therefore necessary to introduce in a clear way the simplifying assumptions made to overcome the lack of information:

- the Missaglia Megabed is simulated with a 110 x 160 x 2 m (width x height x thickness) model that permits to simulate the Megabed and surrounding material up to the contact between Marl and Flysch.
- a distinction is made between tunnels features and geomechanical dataset because the uncertainty in tunnel features is an intrinsic problem for this specific risk and, moreover, the level of confidence of this information is poor. Therefore the variability of tunnel sections is included in the analysis with the use of four different tunnel sections. For each section an outcome is produced. The features of the first tunnel arrangement are reported below:
  - horseshoe-shaped tunnel with a section of 7 x 8 m on all seven levels.
  - first level located at a depth of 45 m.
  - 15 m interval between levels from base to base.

  In the other arrangements tunnel size is progressively enlarged, and only the first level remains fixed at 7 x 8 m, as reported in all historical documents.
- the geomechanical features are defined coupling all available information [32]. When necessary, the geomechanical properties were also integrated with values from the literature [52, 53]. All the properties of Flysch and Marl are reported in Table 4. The uncertainty of these data will be considered only in the next paragraph, with the sensitivity and uncertainty analysis.

  The vertical to horizontal stress ratio, k, was fixed at 1.5 and the Mohr-Coulomb constitutive criterion was applied to simulate block deformation, whereas the Coulomb slip failure criterion was adopted for discontinuities. GSI values provide a geomechanical characterization of Flysch, which is simulated as an equivalent continuum medium because of its peculiar structure.
- external triggering factors are not considered.

Figure 6 shows the outcomes of this analysis. This result clearly displays how enlarged voids induce a state of instability in the system, especially at deeper levels. The stability analysis highlights some kinematic features of the mass movements: the deepest levels are prone to collapse and probably this mechanism consequently trigger progressive failure of the upper parts until the system finds a new equilibrium.

3.3.2 Multiple risk scenario

When uncertainty is not limited to few properties, a probabilistic analysis that takes into account the extreme variability of input data is recommended [54]. A sensitivity and uncertainty analysis may be used to have an overview of the real risk considering the contribution of uncertainties in risk analysis [55].

The stability analysis is considered as the reference case around which the uncertainty and sensitivity analysis are carried out. Sensitivity analysis attempts to define the change in final outcomes due to the variability of input data. A full sensitivity analysis is performed by changing the main properties. Each change was done while the rest of dataset remains constant. In this way the most important input data that mainly contribute to the uncertainty of the risk analysis are defined (Figure 7). The properties ranges explored in the sensitivity analysis are reported in Table 5.

The sensitivity analysis can be summarized as follow:

- Joint cohesion and joint friction have no influence on tunnel convergence at existing confining stresses.
- Joint stiffness and joint persistence are significantly linked to tunnel stability.

Considering the sensitivity analysis, five different sets of geomechanical properties were used in the uncertainty analysis to generate a range of possible risk scenario. As before, the set named as reference case refers to the first hypothesis of stability analysis. The other four sets are defined accordingly with the Table 6.

As before, four representative tunnel dimensions are considered. For the uncertainty analysis a specific attention is paid to the state of “in situ” rock stress, a condition that remains a challenge in many geo-engineering practices. Indeed, the state of rock stress [56, 57] is difficult to achieve even when stress measurements are performed. Numerical simulations were thus conducted for different values of k [58]; vertical stress was estimated considering the overburden material, while a range of horizontal stresses was taken into consideration.

The graphs in Figure 8 report the outcomes of 80 simulations (i.e., the combination of 5 different sets of input dataset with 4 tunnel sections and 4 k values); this Figure highlights how tunnel section and k ratio affect the results.

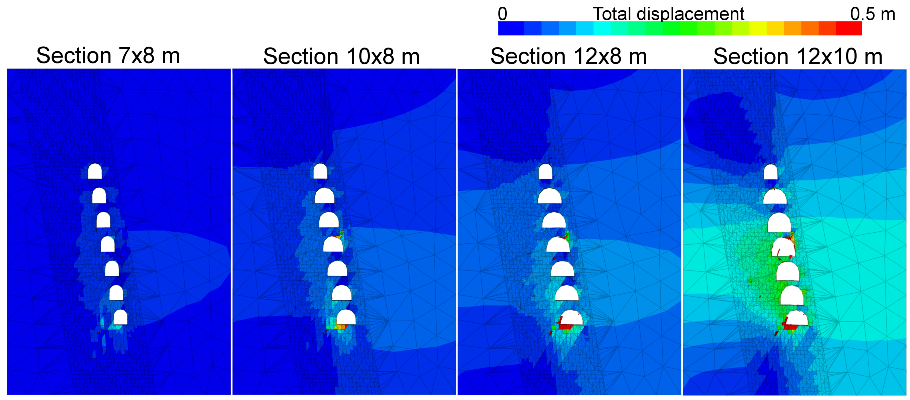

Figure 6: Stability analysis of Montevecchia mine: tunnel convergence of VS tunnel section.

Table 5: Ranges of values of joint and rock mass properties used in the sensitivity analysis.

Sensitivity test	Stability Analysis Value	Variation Interval
Joints Friction angle	30°	From 20°to 35°
Joints Normal stiffness	0.8 GPa/m	From 0.60 GPa/m to 1.00 GPa/m
Joints Shear stiffness	0.4 GPa/m	From 0.30 GPa/m to 0.50 GPa/m
Joints Persistence	0.7	From 0.4 to 1.0
Joints Cohesion	1 MPa	From 0 MPa to 3 MPa

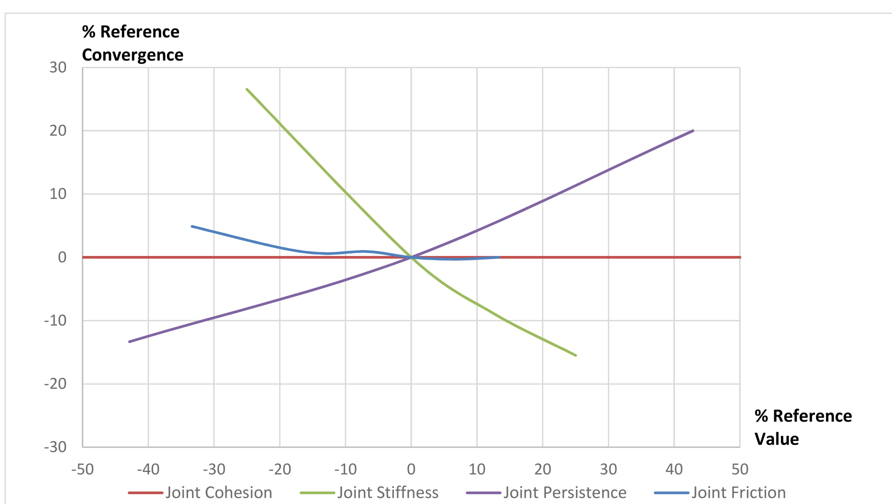

Figure 7: Relation between properties variation and tunnel convergence expressed as percentage of stability analysis value.

Table 6: Uncertainty analysis input geomechanical properties sets.

	Set 1	Set 2	Reference Case	Set 3	Set 4
Joints normal stiffness	0.5 GPa/m	0.5 GPa/m	0.8 GPa/m	1 GPa/m	1 GPa/m
Joints persistence	1	1	0.7	0.6	0.4
Joints Friction angle	20°	30°	30°	30°	30°

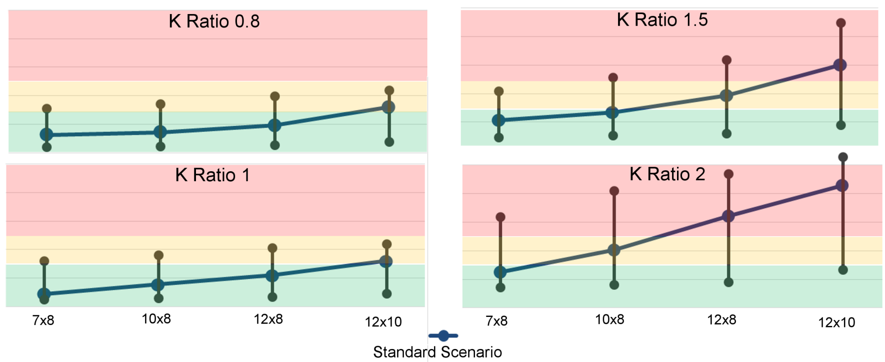

Figure 8: Outcomes of 80 numerical simulations. Each graph represents 20 numerical simulations performed for 4 different k values and 4 tunnel dimensions (7x8, 10x8, 12x8, 12x10 m). The dots in the standard scenario are joined with a line. The other cases are presented in a bar line (from the best to the worst case in terms of stability). The green, yellow and red layers define the three possible risk conditions. Bars highlight maximum variation between the best and worst scenarios.

4 Discussion

Efficient management of any kind of environmental risk requires the definition of a "risk scenario" closest to reality that should be used as the basis for decision-making. This is essential, but, for abandoned mines characterized by great uncertainty, it is difficult to achieve. The problem of poor knowledge can be solved in two ways: the first is to reduce the lack of knowledge through additional research and data collection (often very difficult for logistic and economic reasons), while the second way attempts to conduct a general analysis considering all possible risk scenarios. This second approach fits well the purpose of this work and it is particular suitable for highly unreliable outcomes. Therefore, the solution must be sought in the collection of different data and in uncertainty analysis [55] aimed to generate a set of risk scenarios.

On the basis of the available information and on the integration of sensitivity and uncertainty analysis, a set of scenarios was defined. The results of multiple scenario (Figure 8) were summed considering the reference states (Figure 5) in order to generate an overview of the collapse probability, directly related to tunnel sections. This analysis is reported in the summary graph (Figure 9), that shows the probability of each scenario.

More in detail, the final result may be useful for an overview of the actual residual risk for human settlements located in the western and eastern areas of the mine (Figure 1), which have not yet collapsed as well as for land use and management.

Before starting with the evaluation of the residual risk in Montevecchia mine, the 1958 event was analyzed to validate the summary graph (Figure 9). Considering that historical data reported the central part, where the sinkhole occurred, as the more exploited area with the larger tunnel section, the last case of Figure 9 was considered. As expected the 12x10 m tunnel section shows less than 20% of stable condition, confirming the critical situation that led to the collapse of the central area.

After this validation it was possible to evaluate the residual risk for the other two sections (Figure 9). According to most of the historical documents, the eastern part of the mine was not so heavily exploited and its sections should be 10x8 meters, resulting in a situation of relative stability; it has about a 55% chance of being stable, and only a 20% chance of developing significant instability. The western part has a similar condition, and exploitation was performed on only six levels. Thus this area can also be considered almost stable. Therefore new investigations of the eastern and western areas of the mine site are not currently necessary because the situation seems fairly stable, thus the residual risk in west and east areas of Montevecchia mine is not a priority for land management. Such information will help also to determine if more investigations are necessary. The summary graph in a simple way may allow decision makers to minimize the use of public funds, avoiding expensive studies which a priori are often not useful for a real improvement in the reliability of the final risk scenario.

The assumptions introduced in the previous paragraphs must be considered to evaluate the limit of the approach:

- only three reference states to classify outcomes are taken into account and all the results are linked only with one of these states. Moreover only four different tunnel sections are considered. This is a strong simplification but in order to avoid too many numerical

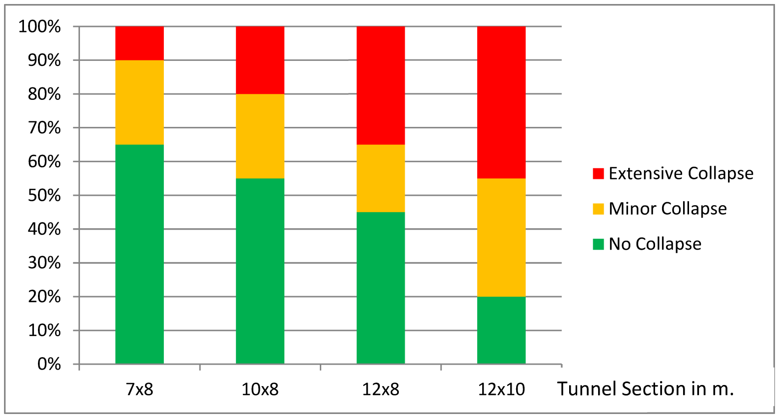

Figure 9: Summary graph of the 80 simulations performed to take into account the variability and uncertainty of input data at the Montevecchia mine site.

simulations a limited number of cases was chosen. Of course this directly affects the results.

– a rigorous probabilistic analysis was not performed. For instance a Montecarlo analysis may improve the analysis of this risk but the numerical analysis could require long computational time and it was not the purpose of this work.
– none model uncertainty related to the code was considered. It could be interesting to test also other codes.
– k value was considered one of the main uncertainties and several simulations were performed for each of this value. Of course a detailed knowledge of this boundary condition may lead to an improvement of the summary graph.
– in general, a better analysis of the geomechanical properties of Flysch and Marl [59] as well as a complete analysis of the geological context [60] may lead to a great improvement in risk analysis.

Considering this limitations, the risk scenario should be refined and updated over time as new data become available. Moreover, to really improve the reliability of this approach, a monitoring system capable of detecting detailed information on rock mass behavior may be used. For instance, remote sensing techniques [61] could be powerful tools for evaluating surface displacements in the area surrounding abandoned mines [62, 63].

5 Conclusion

Geo-hazards related to the long-term stability of abandoned mines located in urbanized areas are a challenge for all countries with a mining history. When underground mines may affect human settlements, it is very important to check the stability of mines, even at sites no longer in use. Nowadays, the risks related with active mines are well known and thoroughly studied, but one of the major problems related to underground mines concerns abandoned mine sites. It may be difficult to obtain all the information required to quantify the risk associated with these voids after mine site closure, especially in the case of old mines without historical documentation. Moreover, neither guidelines nor procedures are currently available for assessing how to approach this problem. In keeping with these environmental problems, long-term analysis of these sites should be planned.

Starting from these considerations, a simple approach is here proposed. The purpose of this approach is to give an overview of the collapse risk of abandoned mine considering how to tackle input data uncertainty. Frequently, in risk analysis a strong interference between uncertainty and decision making is present and therefore it is crucial to generate an easy, accessible and transparent decision procedure capable to solve also complex problem characterized by poor local information. The summary graph fits well the requirements of transparency (the assumptions and the limits are declared and discussed), accessibility (data are reported in the text and, graphs are easier to understand) and ease (the method is based upon an easy and simple approach).

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