

Occupational Safety and Health in Tunnelling in Rocks Formations Potentially Containing Asbestos: Good Practices for Risk Assessment and Management

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Abstract: In tunnelling operations, Occupational Safety and Health (OS&H) and Environmental Protection of the areas close to the tunnel portal become even more critical in case of rock formations potentially containing asbestos, quartz, radioactive elements, etc. In order to limit the workers' exposure and the environmental impact becomes in these cases of paramount importance to preliminarily analyze and quantify the possible presence of the pollutants in the rock and, if necessary, to implement suitable measures to avoid/minimize their emission from the winning and mucking operations. However, in case of asbestos minerals, to obtain reliable results from the preliminary analysis is a challenging task, due to the complex patterns of occurrence of asbestos within the host rock. Consequently, the definition of special monitoring, alarm and control systems is essential during the tunnel excavation. The paper summarizes the results of a thorough study aimed at defining the most suitable monitoring techniques in uncertain situations and the residual criticalities, essentially due to the delay between the beginning of the pollutant release at the tunnel face and its detection. The final part of the work deals with the possible innovative prevention solutions suitable to minimize the previously mentioned delay and ensure the safety of the workers along the time necessary to stop the activities and evacuate the tunnel, on hold of the activation of a special "asbestos" organization.

Keywords: Tunnelling in Rock Containing Asbestos, Occupational Risk Assessment and Management, Environmental Conditions Monitoring, Real Time Fibers Counters, Positive Pressure Respirators

Introduction

According to the BIDPM (2008), any determination has imperfections giving rise to uncertainty in the result. An uncertainty is formed by two components, namely, a *systematic component* and a *random one*.

It is possible to quantify the effect of the *systematic uncertainty* and, if significant, to apply a compensating correction.

Random uncertainty arises from unpredictable stochastic variations (random effects) of the influent quantities and only a substantial increase in the number of observations can reduce the effects of such variations.

In the case of underground infrastructures construction, the random effect can be much greater than

in other industrial activities due to the nature of the input data, tunnelling involving natural elements that often show, at least on a local scale, not constant characteristics.

The geological, hydrogeological and geotechnical-geomechanical uncertainties (Eskesen *et al.*, 2004; Peila, 2009) are here formed by a systematic component bound to *the geological model* and by a random component, due to the localized variability of the excavated rock, even involving the presence of hazardous substances and the deriving pollution of work places and environment.

This, according to the Eskesen's classification, can result in dramatic consequences on the Safety and Health of workers and third parties and seriously harm the surrounding environment. Asides of the image

loss, this may jeopardize the enterprise economic sustainability, due to forced tunnelling stoppages and the necessary introduction of control measures not budgeted in advance. The generalized use of the technical, technological and procedural precautions necessary in confirmed presence of the hazardous substances, however, does not constitute a feasible solution to manage the problem, since costly and heavily impacting on the tunnel driving velocity and intrinsically anti-ecological, due to the unnecessary energy consumption, landfilling of large amounts of material improperly treated as special waste, etc.).

A correct approach to the problem should consist in a throughout preliminary Risk Assessment, to reduce as much as possible both the systematic and the random uncertainties. The target is to identify and quantify the possible presence of hazardous substances in the rock mass and design the necessary Risk Management countermeasures, including the *standard* monitoring and control systems for:

- Normal tunnelling operations (i.e., positive exclusion of the presence of hazardous substances)
- Exceptional operations (i.e., positive presence of hazardous substances)

And the *additional* monitoring, alarm and control systems to be activated if necessary (i.e., in presence of rocks potentially containing hazardous substances).

Table 1 summarizes the actions laying, in the case, at the very base of an effective Risk Assessment and Management, coherent with both good design criteria and law requirements.

The approach to the Hazard Identification strongly depends on the pattern of presence of the different hazardous substances in the host rock:

- In the case of “embedded” substances (e.g., asbestos, silica, radioactive minerals, etc.), detailed area and geological studies, implemented with direct observations and instrumental analyses of samples, are particularly important to gather information on their presence and amount
- In the case of “mobile” substances (e.g., firedamp and other gases, solid particles transported by water, water-soluble substances and gases (radon), etc.) further detailed analyses are necessary, e.g., on general and local fracture layout, presence of even distant formations affected by groundwater movement, etc

In particular, where the “embedded” substances are considered, it is important to verify the adequacy of a geostatistical approach (Matheron, 1963) to analyze and predict their distribution in the rock mass:

- Radioactive minerals and silica usually show a rather uniform distribution, which can be predicted in geostatistical terms
- On the contrary, asbestos minerals do not have a predictable distribution. In fact, the distribution of asbestos minerals is usually highly irregular, since their possible formation during the metamorphic process depends on pressure, temperature, host rock composition and on the structural framework. Asbestos concentrations often occur as “veins”, or show a typical “nugget effect”, related to ductile to (more often) brittle structures like shear zones, fault planes and fractures (Davis and Reynolds, 1996; Perello and Venturini, 2006)

The problem of asbestos containing rocks is of special concern in tunnelling operations through the North Western Alps, as shown in Fig. 1.

Random uncertainty becomes then particularly important (Seingre, 2006) and heavily impacts on the possibility of developing a throughout Risk Assessment and Management (Chromy *et al.*, 2006; Labagnara *et al.*, 2013a), since:

- Even the use of probabilistic analysis for the determination of the risk (Špacková *et al.*, 2013; Wang *et al.*, 2014) does not in this case provide results with the desired accuracy
- The preliminary investigations preceding the tunnel excavation phase, covering literature survey, photogrammetric studies, geological and geophysical surveys and surface drilling and core analysis, make usually possible to *exclude* the presence of rocks potentially containing asbestos minerals, but often a *no sure decision situations* classification still remains

Summarizing, the preliminary Risk Assessment can suggest the four classes of criticality summarized in Table 2.

The current diffusion of full-face tunnelling techniques partly reduces the OS&H and environmental impact problems even in asbestos containing rock formations. Unlike what happens in the case of drill and blast and localized mechanical winning, full-face tunnelling makes in fact possible some control on the rock fragmentation, the immediate muck wetting and dust removal and limited disturbances on the face and tunnel ventilation in the various operating phases.

All the same, for the excavation of no sure decision tracts only the definition of *special* monitoring systems-in addition to the *normal* ones used to improve the knowledge of local geomechanical parameters, preventing water or gas incomes, etc. -makes possible the immediate introduction of suitable safety measures when necessary.

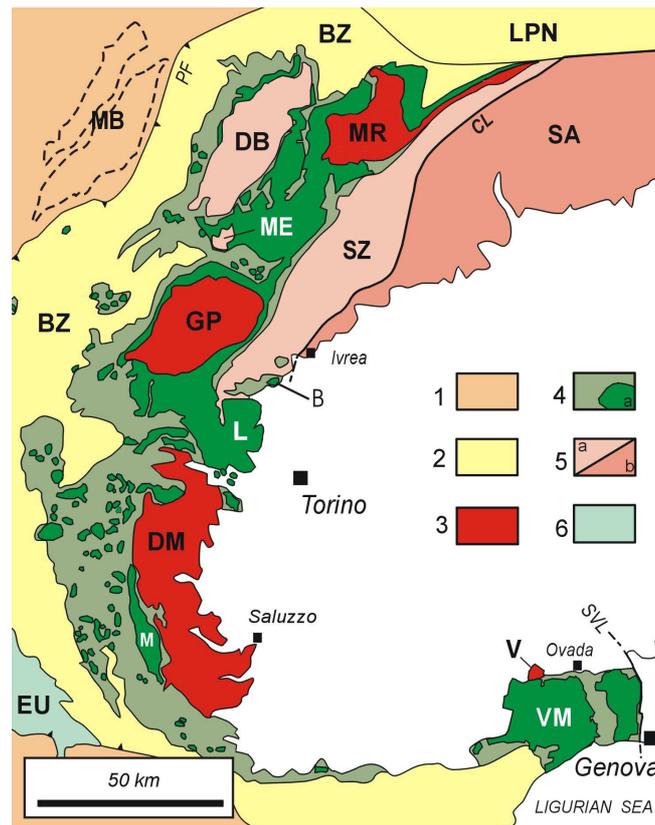


Fig. 1. Simplified tectonic sketch-map of the western Alps. 1: Helvetic Domain (MB: Mont Blanc-Aiguilles Rouges). 2-4: Penninic Domain, 2: Briançonnais Zone (BZ) and Lower Pennine Nappes (LPN); 3: Internal Crystalline Massifs of Monte Rosa (MR), Gran Paradiso (GP), Dora Maira (DM) and Valosio (V); 4: Piemonte Zone (a: Main ophiolitic bodies), L: Lanzo Ultramafic Massif, M: Monviso ophiolites, VM: Voltri Massif. 5: Austro-alpine Domain: a: Dent-Blanche nappe (DB), Mt. Emilius nappe (ME) and Sesia Zone (SZ); b: Undifferentiated Southalpine Domain (SA). 6: Embrunais-Ubaye Flysch Nappe (EU). CL: Canavese Line; SVL: Sestri-Voltaggio Line; PF: Penninic Thrust Front. B = Balangero chrysotile mine. Modified after (Castelli *et al.*, 2002)

Table 1. Steps for an effective risk assessment and management in tunnelling operations

1. Hazards Identification: Forecasting the presence of hazardous substances in the rock mass to be excavated; the prediction should be completed with the best estimate of its uncertainty
2. Risk Analysis: Correlating the result of the Hazard Identification with workers exposure models. The latter should be defined with the best possible detail, taking into account, however, that the diversification of tasks is often quite blurred in spite of the formal job descriptions (in a real case of use of TBM we found 11 official job descriptions, but identified only 3 typologies of actual job)
3. Risk Assessment: The results of the Risk Analysis are here used for decision making, through direct comparison with minimized risk targets (e.g., Occupational Exposure Limits (OELs) values if available (Skowroń, 2013), or relative ranking of effectiveness and cost of different risk reduction measures based on different techniques and technologies
4. Risk Management: Selection of both the most appropriate technologies and techniques for winning, mucking, ventilation, etc. and the management policies, procedures and practices, to grant along the time Occupational Safety and Health, neighboring areas environmental quality and economic effectiveness

Table 2. Classification of underground operations with reference to the asbestos hazard factor deriving from the preliminary risk assessment. The classification represents a useful reference for the definition of Risk Management approaches

Situation inferred from preliminary investigations	Criticality class
Certain exclusion of rock formations potentially containing asbestos minerals	0
Possible presence of rocks formation potentially containing asbestos minerals	1
Confirmed presence of rocks formation potentially containing asbestos minerals-asbestos not already detected	2
Presence of rocks formation containing asbestos minerals-asbestos detected	3

Materials and Methods

In a *no sure decision* situation, a number of implementations to the *normal* monitoring system are necessary. Such additional measures should enable to detect:

- The presence of asbestos in the rock mass as soon as possible (before or following immediately the rock winning)
- A situation of possible exposure of people working in the underground
- A possible pollution from the portal towards the common environment
- The actual amount of asbestos in the excavated rock and, consequently, the muck final destination

A summary of the most common techniques follows.

Exploratory Drillings, Core/Chips and Drilling Fluid Analysis

Core, or cheaper and faster destruction drilling can be used, the selection depending on the preliminary Criticality Class adopted. In both cases, a careful recovery of the drilling fluids is of paramount importance. Obviously, the samples resulting from core drilling require, besides from visual analysis, complex milling and sub-sampling operations, whilst destruction-drilling samples are difficult to analyze and can only qualitatively be placed along the borehole.

The definition of the drillings length and overlap should copy with the tunnel excavation cycle, so that no route tracts remain uninvestigated. In the case of use of a TBM, to prevent interference with the tunnel excavation the drillings can diverge in some cases from the tunnel axis and their number is very limited. Figure 2 shows the realization of an exploratory destruction drilling from a small size open TBM (approx. 6 m dia.).



Fig. 2. Exploratory drilling from the top level of an open TBM. Note the narrow space available for the drilling and samplings recovery operations

Direct Geological Analysis of the Tunnel Face and Walls

These investigations should be repeated with a frequency depending on the previously assigned criticality class, up to 24/24 h if the situation is assumed critical.

Special, Personal and Environmental Samplings of Airborne Fibers

It is first necessary to point out that the current techniques of accurate determination of dust and airborne fibers concentrations are based on two stages operations: Separation by filtration of the sample from the air, followed by laboratory analysis (Phase Contrast Microscope-PCM according to (WHO, 1997; IOS standard 8672, 2014), or Scansion Electron Microscope-SEM according to (IOS standard 14966, 2002).

Special dust and airborne fibers samplings, to get information on the presence of asbestos in the rock mass: Samples collection in the proximity of the dust emission point can be very useful. Figure 3 depicts the possible schematic of isokinetic sampling (IOS standard 10397, 1993) in the suction duct of an open TBM. Obviously, the total dust content and the air velocity in the duct condition the sampling duration, whilst the sampling frequency depends on the preliminary Criticality Class adopted.

The frequency of the *personal samplings* also depends on the preliminary Criticality Class adopted and on the excavation rate. Since: (a) The environmental sampler's intake velocities are predetermined for both inspirable and respirable particulates and fibers; (b) the sampling should cover typical activities, to collect a quantity of material suitable for the analysis and to infer exposure conditions, the samples duration ranges from 3 to 8 h. Figure 4 depicts a personal sampling for asbestos in the cockpit of an open TBM.

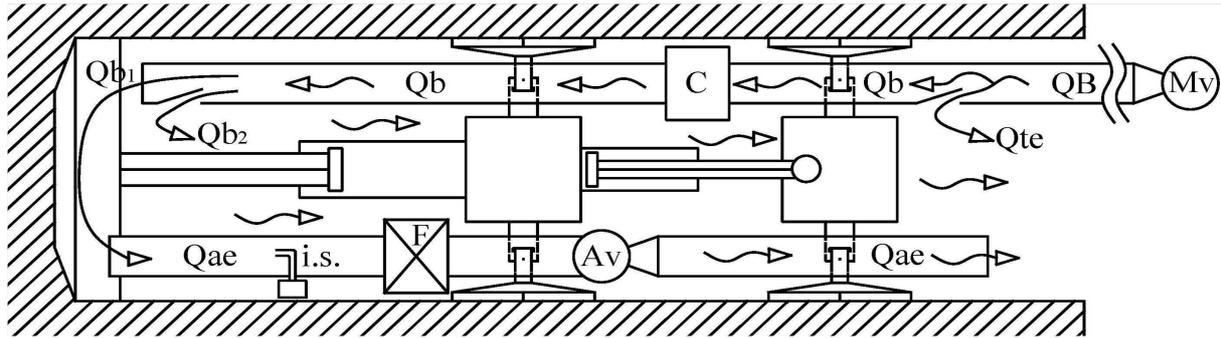


Fig. 3. Example of the possible isokinetic sampling point in the exhaust duct at the face of an open TBM driven exploratory tunnel. Mv: main ventilator. QB: Total blowing airflow. Qb: onboard blowing airflow. Qb1: Face airflow. Qb2: Motor cooling airflow. Qte: Backup and tunnel airflow. C: Chiller. Qae: exhaust airflow. Isokinetic sampling (Is): Filter (F): Auxiliary ventilator (Av); $QB = Qb + Qte = Qb1 + Qb2 + Qte$; $Qb1 < Qae$



Fig. 4. Personal sampling for asbestos fibers, in the cockpit of an open TBM

Finally, the *environmental samplings* make available a continuous monitoring of the possible emission of pollutants from the yard. Since also in this case the sampler's intake velocities are predetermined, the sampling duration is of 5÷8 h. Figure 5 shows an asbestos sampler for environmental samplings.

Sampling of the Muck

Essential to decide its destination (reuse or storage in landfills of officially defined categories and characteristics). The sampling frequency depends on the amount of excavated material (obviously bound to the excavation rate).



Fig. 5. Asbestos sampler for the environmental samplings in a tunnel yard

Table 3 summarizes the monitoring systems suitable for tunnelling with an open TBM in no sure decision situations (risk class 2).

Table 3. Example of integrative monitoring system, suitable for tunnelling with an open TBM in Risk Class 2 (presence of rocks formation potentially containing asbestos minerals-asbestos not already detected). Note 1: A larger number of exploratory drillings is difficult to organize and does not contribute substantially to increase the representativeness

Monitoring technique	Frequency of the analyses	Sampling duration	Time required for the analysis
Exploratory drillings (1): -core/chips and drilling fluid sampling -direct (visual) or laboratory analysis	Continuous, with variable overlapping	Less than 2 h for 100 m long destruction drillings More than 2 h and dependent on the diameter and rock for 100 m long core drillings	Real time for visual analysis; at least 1 day (sampling, core and chips grinding, deposition on support filter and analysis with PCM or SEM)
Direct geological analysis of the tunnel face and walls	Continuous, implies the 24/24h presence of a geologist at the face	---	Variable, conditioned by a series of parameters including the tunnel diameter, the TBM characteristics, etc.
Particulates sampling in the proximity of the rock winning area	Isokinetic samplings every 2 m progress	Approx. 1 h/sample	PCM analysis: Approx. 2 h, including the sample preparation
Personal samplings to determine the workers' exposure	In continuous if technically and organizationally feasible	From 3 to 8 h: Usually with a flow from 1 to 3 l/min., for a total of at least 480 l.	PCM analysis: Approx. 2 h, including the sample preparation
Environmental samplings	In continuous	From 5 to 8 h: Usually with a flow from 6 to 10 l/min., for a total of at least 3000 l.	For SEM analysis: Approx. 4 h for the analytical phase, including the sample preparation
Sampling of the muck (visual and instrumental analysis)	Approx. every 5000 m ³ progress	Unspecified but not easy (Bozzola and Patrucco, 1992)	Variable, conditioned by the sampling techniques of the muck piles and by the preparation of the final samples for the analysis

Results and Discussion

The proposed integrative monitoring approach is technically feasible and exhaustive, but, whatever the system, the practical result depends dramatically on the delay between the beginning of the pollutant release at the tunnel face and its detection.

A number of delay causes can rise, the most common for the above discussed sub parts being.

Exploratory Drillings, Core/Chips and Drilling Fluid Analysis

The representativeness of the result can be affected by the possibility 'to miss the mark', i.e., the random distributed asbestos containing veins; secondly, sample losses can occur during the chips and drilling fluid recovery in difficult operating conditions.

The delay between the occurrence of the problem and its detection can range from a few minutes if the yard geologist visually identifies the presence of asbestos, up to 24 h to receive a reliable result from the yard laboratory, if directly available, plus the sample dispatching time, in case of reference to an external laboratory. A suitable value of the drillings overlap can limit the impact of such delays on the work program (e.g., in the case of: 20 m/day tunnelling rate, exploratory drillings 100 m long and minimum overlapping of 20 m, the laboratory results are still available in time to introduce corrective measures where necessary).

Direct Geological Analysis of the Tunnel Face and Walls

The delay between the occurrence of the problem and its detection: Even if an open TBM is used (a good choice in the case of exploratory geognostic small diameter excavations) presumably the geologist can analyze occasionally the face in no production situations and the walls at the back of the cutter head, i.e., approximately 5 m far from the face. Considering the previously assumed 20 m/day excavation rate, at the best the geologist may become aware of the presence of asbestos after more than 5 h.

Neither the implementation of a system for automatically collecting samples from the hopper of the head conveyor, a good idea since it allows the geologist to examine the excavated material in almost real time, can be considered completely exhaustive due to the very limited representativeness of the samples, in particular in the fine components of the granulometric distribution.

The possibility of errors in a subjective evaluation in difficult conditions: The geologist can give an inaccurate indication. The excavation continues without the adoption of countermeasures as long as and only if, the results of the airborne pollutant samplings highlight the problem.

Special, Personal and Environmental Samplings of Airborne Fibers

The delay between the occurrence of the problem and its detection: For the special and personal samplings,

even in the case of continuous sampling (hardly feasible from a technical, organizational and economical point of view), the time necessary to obtain the measured value is the sum of the sampling, sample dispatching and analysis times. A minimum delay between pollution occurrence and information can then be more than 5 h.

In the case of *environmental samplings*, the delay is even higher, due to the longer sampling time.

With reference to the *representativeness of the results*, we should consider that: (a) Since, as mentioned, the *special* and *personal sampling* are seldom continuous, some critical situations may remain totally undetected; (b) the *environmental samples* are in many cases collected far from the tunnel portal or even outside the yard. Thus, variables of difficult characterization, not necessarily related to the tunnelling activities, may influence the results, which cannot thus constitute a reliable warning of an undetected pollution in the underground.

Sampling of the Muck

Special care is necessary to grant the samples representativeness, otherwise both serious problems of OS&H for the re-users and heavy environmental impact can arise.

Moreover, it should be remembered that Standards on asbestos samples analysis methods (mainly based on PCM or SEM techniques) are widely available, but the standardization on sampling procedures is less common. In particular, the Italian standardized procedure for samplings of muck (ILB, 2006) is hardly applicable to a non-homogeneous pollutant and nowadays a standardized sampling procedure for drilling core/chips is not available.

In the case of drilling cores samplings, the choice falls between statistical or judgmental procedures, both with positive and negative aspects (Labagnara *et al.*, 2013b):

- The *statistical approach* involves collecting samples at a pre-defined interval along the core length. This approach is objective but involves the possibility of an underestimation of the asbestos content if the veins are not localized at the sampling points
- The *judgmental method* is entrusted to the decisions of the analyst, who shall define homogeneous tracts of the core and decides where to collect the samples. The quality of the result depends on the analyst's expertise

Starting from the case in which the drill-hole does not intercept the critical vein, or of incorrect results of the visual analysis of the core/chips and fluids samples, the duration of the consequent uncontrolled dispersion may extend among:

- More than 3 h in the case of evidence from airborne samplings in the proximity of the rock winning area
- More than 5 h in the case of visual identification of asbestos on the tunnel walls
- Even longer if we have to wait for the results of the airborne asbestos samplings and analyses

Such delays might seem at first sight not critical, but it is not so, as demonstrable by the following simple calculation developed by way of example. We assume that a vein containing 100 kg of fibrous tremolite (2% of the total mass of the vein) is present along the route of a 100 m² cross section tunnel in serpentinite; the vein thickness is 1 cm, the trending 90° and the dipping 25° to the tunnel axis. In the hypothesis that 10% (10 kg) of the tremolite becomes air dispersed as respirable fibers (e.g., $L/\varnothing = 5$, $L = 10 \mu\text{m}$, $\varnothing = 2 \mu\text{m}$) due to the winning operations, *a dispersion of fibers higher than $1 * 10^{14} \text{ fb}$ will occur!*

The Event Tree Analysis technique (CCPS, 2008) applied to the proposed special monitoring system in an open TBM tunneling operation provides the results summarized in Fig. 6.

An ideal approach to avoid uncontrolled pollution of the underground workplaces and emissions from the tunnel portal would be to identify in a very short time (i.e., in a single stage, directly in the yard areas) the presence of airborne asbestos fibers. A throughout investigation proved that no instruments suitable for such measurements are to date available on the market and the ones under development (Stopford *et al.*, 2013) are incompatible with the temperature, humidity and pollution conditions typical of the underground yards.

Since some years however, field tests of total fiber counters provided encouraging results even in difficult environmental conditions (Kauffer *et al.*, 2000; 2003). These instruments cannot substitute the traditional analyses of sampled particulates, however necessary for both the calibration of the method and back analyses, but they can play an extremely useful role in the almost immediate identification of pollutant emissions and concentration trends, if either of the following conditions is satisfied:

- The average concentration of non-asbestos airborne fibers during the different operations in normal conditions, if any, is already known from previous investigations, so that we can reasonably ascribe any significant sudden increase in the total fiber count to an emission from the face
- A second fiber counter in the inflow ventilation duct provides a “white” reference value, so that important differences between the fiber count in the incoming and underground air confirm an emergency.

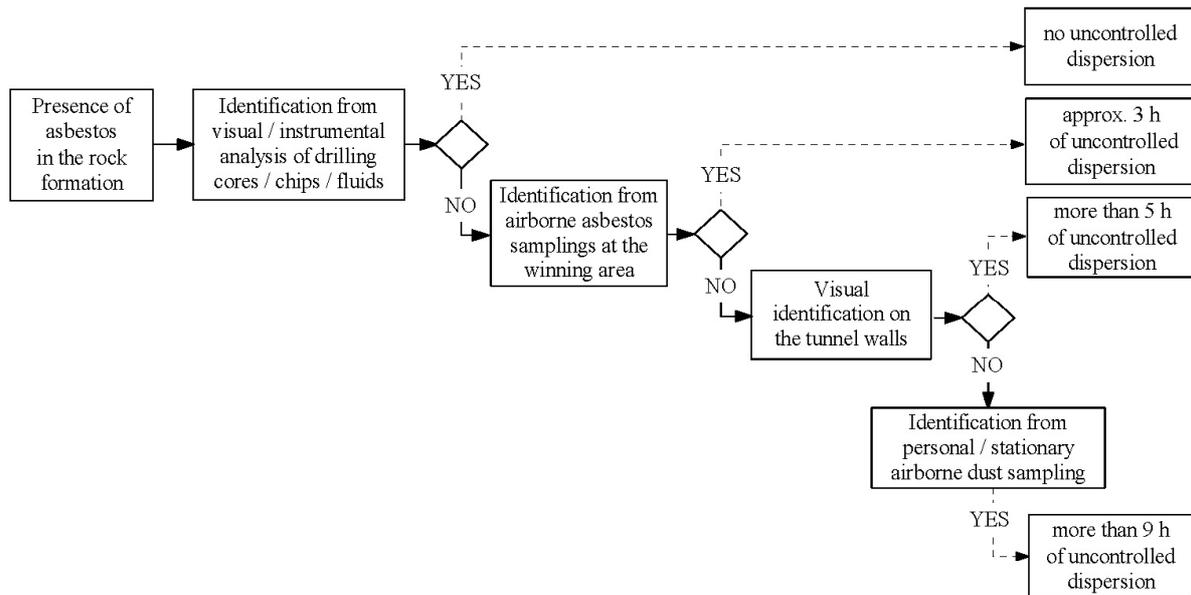


Fig. 6. Event Tree Analysis on the delay between the beginning of the pollutant release towards the tunnel face and its detection. The analysis deals with the case of: Open TBM, 20 m/day excavation velocity, continuous airborne asbestos sampling, 24/24h presence of geologists in the excavation area

Table 4. Summary of the comparative analysis of different powered air purifying respirators. The hood type respirators are not included within the analysis, since specific for laboratory activities

Mask powered air purifying respirator		Hood/helmet powered air purifying respirator			
Half-mask		Full-face mask		Helmet	
Benefits	Disadvantages	Benefits	Disadvantages	Benefits	Disadvantages
Comfort: The PPE is minimally invasive and light, does not interfere with the protective helmet and with glasses; also the visibility and mobility problems are negligible	Due to their conformation, half-masks cannot have a high operational protection factors.	Can grant high operational protection factors.	Can reduce the workers' mobility and vision; interferes with the presence of glasses or helmet; "dirty visor" problems impose <i>tear-off</i> .	Integrates two different PPE; creates a fresh airflow towards the worker's face; glasses or beard do not modify the protection efficiency.	Can reduce the workers' mobility and vision requiring <i>tear-off</i> . The operational protection factor is lower than in type one full-face masks;

The authors recently started the preliminary phases for a test of a last generation fiber counter onboard an open 6 m dia. TBM tunnel, to:

- Identify the best placing for the instrument, taking into account both the technical feasibility and the localized air movements, to grant the representativeness Vs the workers exposure conditions
- Field test the compatibility of the instrument with the local environmental parameters (mainly temperature, humidity, vibration) and the concentration of general airborne dusts
- Define the operating settings most suitable in the case, with particular reference to recirculation and response time (the initially set flow rate is 2 l/min.

with a recirculation of 0.2 l/min.; the minimum response time is 1 min.)

- Define the organization of the subsequent analyses on the outlet filter of the counter

Besides, since in any *no sure decision situation* we still need adequate health protection for the workers along the time necessary to detect the presence of airborne fibers at the underground workplaces, some preliminary tests of helmet type powered air purifying respirators (Fig. 7) are at present ongoing in the same tunnel.

The first essential characteristic is that the fan/filter system, in addition to high reliability, ruggedness, fit and functionality, should ensure an adequate and uniform air feeding (> 160 l/min. for a 8 h work shift).



Fig. 7. Helmet type powered air-purifying respirator (manufacturer Sundström Safety, helmet SR 580, fan unit SR 500)

Table 4 summarizes the PPEs selection criteria: besides from the compliance to the operational protection factors pf (ECS Standard EN 529, 2005), we considered mask (ECS Standard EN 12942, 1998) and hood or helmet (ECS Standard EN 12941, 1994) type powered air-purifying respirators.

The main target of the tests is a data collection on the devices suitability to the task in terms of duration of efficiency, hindrance, usability and comfort in a 8 h shift, etc., in tunnelling operations in narrow, hot and damp work environments.

To this aim, we prepared a specific form, to record the following information:

- Before each work shift:
 - Data on the particular PPE under test (identification code, preliminary maintenance, total hours of use, etc.) and its operating parameters
 - Data on the user (name, specific anatomical features, etc.)
- During the work shift:
 - Working area (winning area, mucking operations, along the tunnel, etc.)
 - Specific task and subtask duration and occasional peculiarities
 - Notes on any special progress situation

- Information on the environmental parameters (temperature, humidity, etc.) and airborne dust concentration (the latter from a personal sampling covering the test duration)

- After the work shift:

- Data on the performance of the device (battery drain, clogged filters, malfunctions)
- Subjective data from the user (discomfort, visor misting, hot, breathing difficulties, etc.)
- Notes

Some preliminary tests already concluded confirmed the suitability and exhaustiveness of the form.

Conclusion

The approach to tunnelling design must necessarily take into due account the possible presence of rock formations containing critical minerals, as typical in the NW Italian Alps. This situation can in fact imply important problems in terms of OS&H and environmental impact, which both require special Risk Assessment and Management, corrective actions following exposure and dispersion into the common environment being clearly not acceptable.

If the presence of asbestos is possible, the preliminary Risk Assessment from geological surveys and long exploratory drillings from the surface can exclude the presence of rocks potentially containing asbestos, but a *no sure decision situations* classification often remains.

In such cases, the normal monitoring systems used to improve the knowledge of local geomechanical parameters, preventing water or gas incomes, etc. are not sufficient.

The implementation of the special monitoring systems here discussed is essential to reduce the delay between the beginning of the pollutant release at the tunnel face and its detection and to make possible an as immediate as possible introduction of suitable countermeasures.

Some new generation detection devices are today available and the authors recently started the preliminary phases for a test onboard an open 6 m dia. TBM tunnel.

In addition, since the goal of a zeroed delay is objectively unattainable, some preliminary tests of helmet type powered air purifying respirators are already ongoing in the same tunnel.

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Author Contributions

The work summarized the results of a study resulting from the joint cooperation of all the authors.

Conflict of Interest

The Authors confirm the non-existence of conflicts of interest regarding the realization of the work.

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