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Firedamp Explosion during Tunneling Operations: Suggestions for a Prevention Through Design Approach from Case Histories

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The effective management of Safety and Health conditions at workplace and pollutant emissions out of tunnel portals is a concerning problem in tunnel driving operations, and the Prevention through Design -PtD- approach seems to be the only suitable way to correctly manage such a situation, even more where firedamp, asbestos, radioactive minerals, etc. should be expected, due to geological reasons.
Due to the dramatic consequences of a firedamp explosion, the Safety and Health conditions in tunneling operations in possibly gassy formations should be based during the different construction phases on an effective Prevention through Design approach and a careful Risk management. Both PtD and Risk Management should in these situations cover also the Human Error possibility in a System Approach according to the Reason's suggestions.
Some helpful advice for proactive actions in both stages (design and underground operations management) can be drawn from a throughout analysis of case histories.
The paper discussed in detail the results of a study developed to provide effective guidelines for a suitable approach to the firedamp problems in tunneling operations, based on the analysis of case histories.

1. Introduction

When workers' Safety and Health -S&H- problems, and effective management of the pollutant emissions from the portal are analyzed with reference to tunneling operations, a correct approach should be based on the logical and mandatory phases listed in the following hierarchic order, Table 1:

Table 1: Logical phases for an effective approach to S&H and common environment pollution problems

Prevention
Control of the pollutant emission (through a careful selection of the tunnel driving techniques and technologies)
Control of the pollution due to emissions into the working environment
Environmental pollution at workplaces (pollutant dilution and air substitutions) / polluted air exhaust (out of the portal), management by means of specially designed ventilation systems
Special working environments (remote control from a safe position)
Protection
Personal Protection Devices

More than 30 % of Italy consists of mountain areas, in two main lines: the Alps, Northern Italian boundary, and the Apennines, which extend from NW to the South of the Country: consequently, tunneling in Italy is a quite important topic in the development of the motorway and railway systems.
Tunneling through the core formations of the Alps interest mainly metamorphic rock, and involve important overburden, difficult rock characteristics, temperature problems, possible water inrushes and the presence of

highly noxious minerals; moreover, in tunnels approaching the Alps and through the Apennines, marl and marl-clay rocks can be met, with possible presence of firedamp.
Some cases of explosion of firedamp during the tunnels excavation have already been analyzed; see in this regard Ramage (1995), and Copur et al. (2011), which analyze firedamp explosions during tunneling with the use of Tunnel Boring Machines.

2. Case histories

2.1 Case history 1: firedamp explosion in underground

The event occurred in a tunnel of approximately 100 m^2 cross section at approximately 4 km from the portal. The tunnel driving was based on the design assumption that every underground activity should be stopped in the case of firedamp concentrations exceeding ≥ 1 % (the Lower Explosive Limit -LEL- value being 5 %). In the accident area, the rock formations were classified “zone 2” (a place where it is unlikely that an explosive atmosphere is present during normal operation but, in the case, it will persist for a short period).
At the time of the event the implementation of the final lining was in progress, using a mobile form of 12 m length, positioned at a distance of approximately 10 m from the tunnel face.
The 2.5 m diameter duct of the blowing tunnel ventilation system ended at approximately 35 m from the lining form, i.e. at approximately 60 m from the face. The form itself causes an important aerodynamic resistance due to the reduction of the free section of the tunnel, so that in practice no effective ventilation was possible in the face area. Figure 1 shows the result of a Computational Fluid Dynamics simulation test: it is possible to observe that the constriction due to the lining form dramatically reduces the air speed in the area between the tunnel face and the form itself. In particular in this volume the speed of the air is lower than 0.3 m/s.
According to the accident analysis results, achieved by means of a computer-assisted technique, the growing level of concrete in the lining area caused the extrusion of firedamp-polluted air from the interspace between the rock and the waterproofing tissue placed on the sides and crown of the tunnel.
A laminar emission of firedamp towards the upper part of the tunnel between the tunnel face and the lining form produced a 4 m^3 layer less than 1 m thick of air-firedamp mix in the area previously described as no significantly ventilated. The mix gave rise to an explosion that involved four workers who suffered important injuries.
The trigger cause was not well defined, possibly a metal-to-metal impact during current operations.
The accident analysis led to the following considerations regarding the main root causes, in particular with reference to the risk assessment and management. A poor risk assessment did not put in evidence the presence of very limited incomes of firedamp in the area, and the possibility of laminar extrusion of the gas due to the progressive rise of the concrete in the interspace between the form and the waterproofing tissue towards the tunnel ceiling. As a consequence, a poor risk management was adopted.
A correct approach required a very careful ventilation design, to grant no still air areas, whilst, in the case, the area from the tunnel face to the lining form was not significantly reached by the ventilation, due to the throttling effect in the reduced section.
The absence of fixed gas detectors able to automatically provide information on the gas concentration, and the unsuitable organization, information, formation and training of the operators charged of manual monitoring contributed to the event.

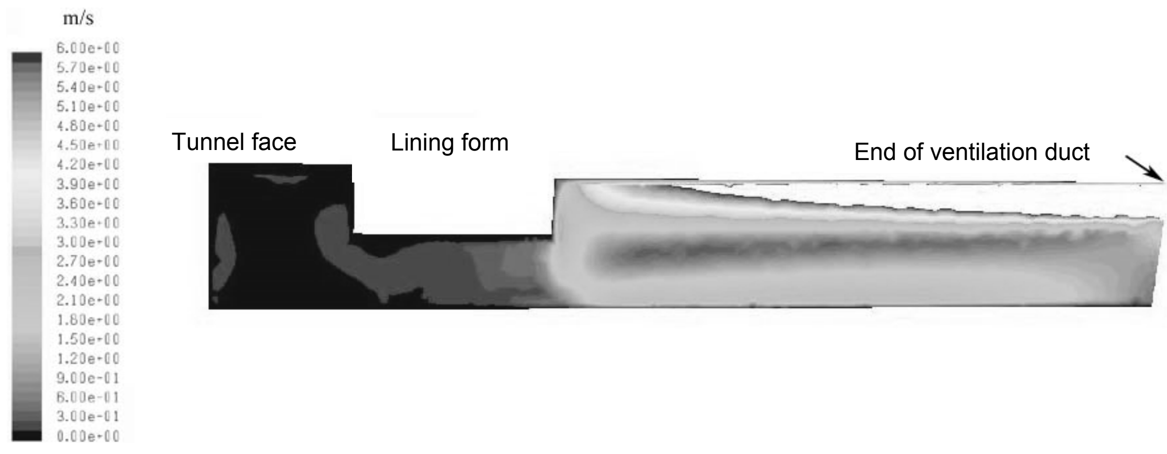

Figure 1: Result of the Computational Fluid Dynamics -CFD- simulation test

2.2 Case history 2: use of Tunnel Boring Machine - Earth Pressure Balance (EPB) in potentially gassy formations

The study was aimed to analyze the preliminary choices, and provide guidance on the specific characteristics for a Tunnel Boring Machine - Earth Pressure Balance (EPB)[1] (already marked in accordance with EU Directive 42/2006/EC on machinery (The European Parliament and of the Council, 2006)) for its use in ground potentially containing firedamp.
The issue has been developed assuming a situation where:

- according to official regulations, exclusively a no explodible atmosphere can be accepted in underground (the LEL value should not be reached);
- the tunneling is developed in “zone 2” situation.

Some key points arose during the analysis were:

1. To avoid explosions in the excavation chamber, the machine should operate only with the chamber always as full as possible. In such a situation the pressure and the presence of the mixture of excavated material, additives and water can ensure that, even with the presence of bubbles of firedamp, the possibility of triggering and propagation of an explosive reaction are minimized. The excavation chamber should also be equipped with a system for detecting the firedamp concentration in the upper part. This system makes possible an immediate action to face possible problems, acting on the parameters of advance rate of the TBM. All seals between the excavation head volume, main drive and bearings should be carefully kept clean and greased;
2. The auger should be equipped with a double lock, in order to block the muck flow from the excavation chamber to conveyor belt on the machine in the case of firedamp presence;
3. The primary conveyor belt onboard the machine should be inserted in a containment structure with double wall in overpressure, equipped with ventilation and flow monitoring systems. In the case of presence of firedamp the advance rate should be automatically reduced (or zeroed in the most critical situations);
4. To prevent the income of firedamp directly through the rock to the tunnel, special seals between the precast segments should be used, and particular attention should be paid to the gap between the shield of the TBM and the ring of precast segments just set in place (in addition to the adoption of specific brushes and greasing it is necessary to maintain this zone in overpressure by means of compressed air);
5. The execution of exploratory drilling in the rocks of the tunnel face involves the possibility of leakage of firedamp from pockets under pressure in the rock towards the area of the shield and the back-up of the machine. Since in a short time a potentially explosive atmosphere in these areas can occur, the same should be tout court classified as “explosion hazard areas”;
6. All the facilities and the equipment used in the potentially critical zones listed above, and all essential systems (emergency lighting, emergency communication devices, gas detection and alarm devices, etc.) should be at least classified in category M2 (High level of protection, EU Directive 94/9/EC on equipment and protective systems intended for use in potentially explosive atmospheres);
7. Finally, as a result of a CFD analysis, the entire TBM should be equipped with sensors for the detection of firedamp, in particular in areas such as the muck discharge point from the auger onto the primary conveyor belt, and along the containment structure of the belt itself. The monitoring of the concentrations of firedamp should be displayed both in the cockpit and outside the tunnel, so allowing a further vigilance on the situation.

The machine tunneled in Italian Apennines two parallel sections of a tunnel of approximately 15 m diameter for a total of 5000 m in length in partly firedamp containing rock formations with neither problem in the management of the critical situations or troublesome false alarms.

3. How to face the possible presence of firedamp in tunneling

To face correctly the problem of firedamp in tunneling it is important to start the work with a detailed Risk Analysis, to investigate aspects related to the possible criticalities. This analysis should:

1. Support the technological and plant choices in the decision making design stage;

1 The TBMs EPB type are shielded machines used in non-compact soil. The TBM EPB minimizes the loss of stability of the tunnel face by means a counter-pressure, provided by the same excavated material with added additives in the excavation chamber. To extract the plasticized material from the chamber an auger is used, which transfers the material onto a primary conveyor belt onboard the machine, which in turn conveys it towards the main conveyor belt operating along the tunnel. After each advancement phase of the machine, a ring of precast segments is positioned, to form the tunnel lining.

2. Provide detailed information on the:
    a. Real distribution of air flows in the various volumes of the underground, to be analyzed with CFD simulations in different ventilation situations. With the use of these data, it is possible to manage the critical zones with proper technical measures. The use of hypothesis or procedures not supported by analysis should be avoided;
    b. Failures cause and consequence of the components of monitoring and managing system (e.g. faults in gas detection system, ventilation system, etc.), and failure rates;
    c. Possible consequences in the case of lack of adequate supplying of energy, air, etc.;

Summarizing, for a comprehensive Risk Analysis the following steps are necessary:

- identification, analysis, assessment and management of the possible critical scenarios during the tunneling in the case of gassy atmosphere possible presence;
- identification, analysis, evaluation and management of deviations (and errors) that in the aforesaid circumstances may affect the safety.

The work should be based on:

1. identification of the Hazard Factors: this involves the use of techniques, such as:
    a. *What If Analysis*, which allows to highlight the consequences of systematically assumed deviations, to identify the countermeasures necessary to reduce the probability of occurrence or mitigate the consequences;
    b. *Failure Mode and Effect Analysis* -FMEA- and *Failure Mode, Effects, and Criticality Analysis* -FMECA-, which systematically analyze the potential failures of the different sub parts of the system, their causes, their effects and the possible corrective actions;
    c. *Hazard and Operability Analysis* -HAZOP-, which allows to evaluate any possible deviation, due to malfunctions or changes in functional parameters, to identify their causes and consequences, and estimate their expectable effectiveness;
2. For each Hazard Factor identified in point 1. discussion of the possible directly related accidents, and of the chain of concatenated events which can lead to the most undesirable outcomes (Top Events);
3. Estimation of the involved Risk, from an evaluation of the probability of occurrence of the considered scenarios. At the purpose, a *Fault Tree Analysis* -FTA- can be used;

Not arbitrary decisions on the technical countermeasures can be made only if these information are correctly collected, but in any case it must be taken into account that not even the aforesaid approach can always grant the possibility of a zeroed risk result.

As a consequence the procedural measures also become of great importance. During their preparation the Human Error also should be taken into due account and managed like any other deviation, and, in accordance with Reason (2000) and with the logic, it is important to highline that where the human errors can lead to catastrophic consequences it is necessary that the human action has only a passive role. A typical example is “alarm that requires operator action” situation: in the case of inaction or misacting by the operator, the system should proceed independently towards a safe condition.

4. Example: application of Hazard Identification Techniques for the Risk Analysis of the ventilation system in tunneling with the possible presence of firedamp

In the case of possible presence of firedamp in the underground, the following parts and components (Table 2) should compose a ventilation system.

Table 2: Parts and components of an underground ventilation system

Subsystem	*Parts*
V – ventilation	*Air movement activators, Air conveying devices*
R – ventilation flow regulation	*Regulation devices*
C – signal processing and response output	*Signal interpretation system*
M – monitoring and detection	*Ventilation performance monitoring devices, Underground pollutant measurement devices, Measurement devices of pollutant emission towards the areas surrounding the tunnel portal, Signal transmission systems*
A – alarm	*Alarm subsystem components (sirens, flashing lights, etc.)*

The ventilation (*V*) settings are regulated by the flow regulation *(R)* on the basis of data fed to the signal processing and response output (*C)* by a gas concentration continuous monitoring system (*M*). The ventilation system to be used is the double flow ventilation layout (Figure 2).

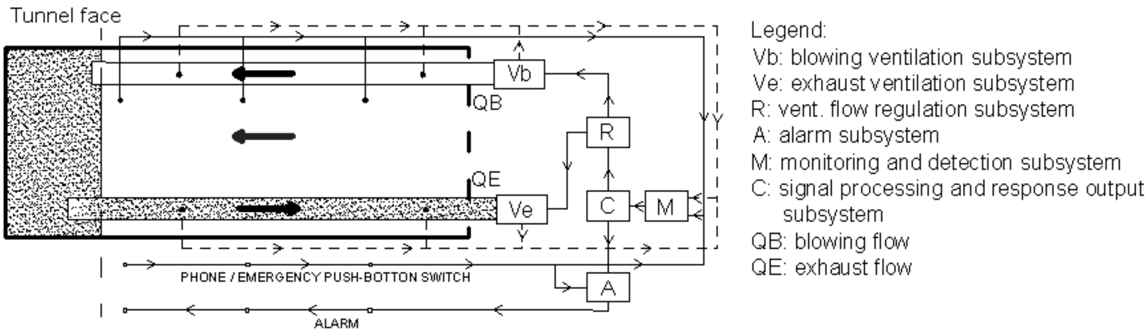

Figure 2: Double flow ventilation system layout (QE > QB)

4.1 First step: HAZOP - Hazard and Operability Analysis

As a first step of the Hazard Identification process, a systematic analysis using HAZOP technique was used to bring into evidence the possible deviations of the ventilation system, and their qualitative consequences, leading to the singling out of the most undesirable outcomes (Top Events).
The HAZOP analysis (Table 3 shows an extract) is based upon the process variables in Figure 3.

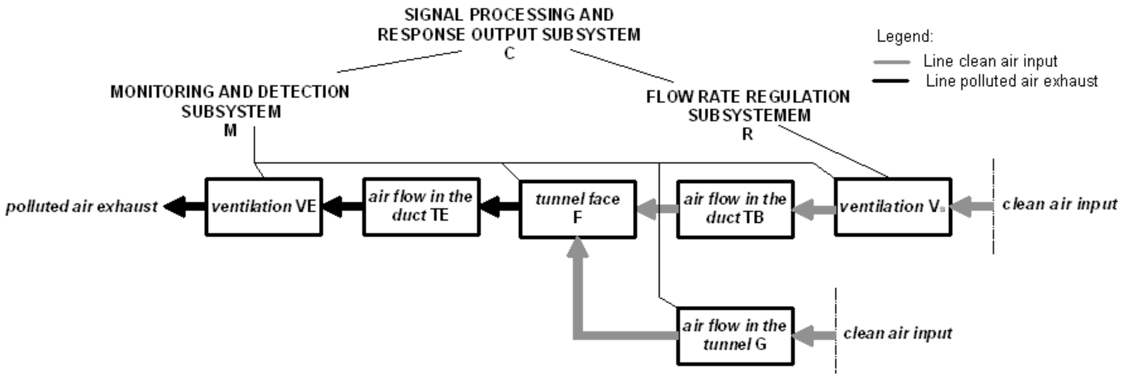

Figure 3: Identification of the main process variables for a double flow ventilation system

Table 3: Extract of HAZOP for a double flow ventilation system layout

Processes	***Parameters***	***Deviation***	***Causes***	***Effects (worst credible case)***
Ventilation V_B	Q clean air 1	No	Fan failure	Formation of the explodible atmosphere scarcely contrasted by the ventilation system
		Less	Worn fan	Formation of the explodible atmosphere scarcely contrasted by the ventilation system
		More	Improper adjustment of fan	Thermal discomfort, raising dust
…	…	…	…	…
Monitoring and detection M	Data	No	Gas detector failure	Formation of the explodible atmosphere not contrasted by the ventilation system
		No	Gas concentration signal transmission system fault	Formation of the explodible atmosphere not contrasted by the ventilation system
…	…	…	…	…

4.2 Second step: FTA - Fault Tree Analysis

To analyze the interactions among the identified Initiator Events, both qualitative and quantitative FTA were used (Figure 4). We assumed as Top Event the formation of explodible atmosphere not contrasted by the ventilation system. Such an assumption, related to the block of the gas dilution, makes possible to efficiently analyze the system response to a fault, and correctly excludes parts, as Ventilation performance monitoring devices and Alarm subsystem, which are important only where the adopted Top Event already occurred.

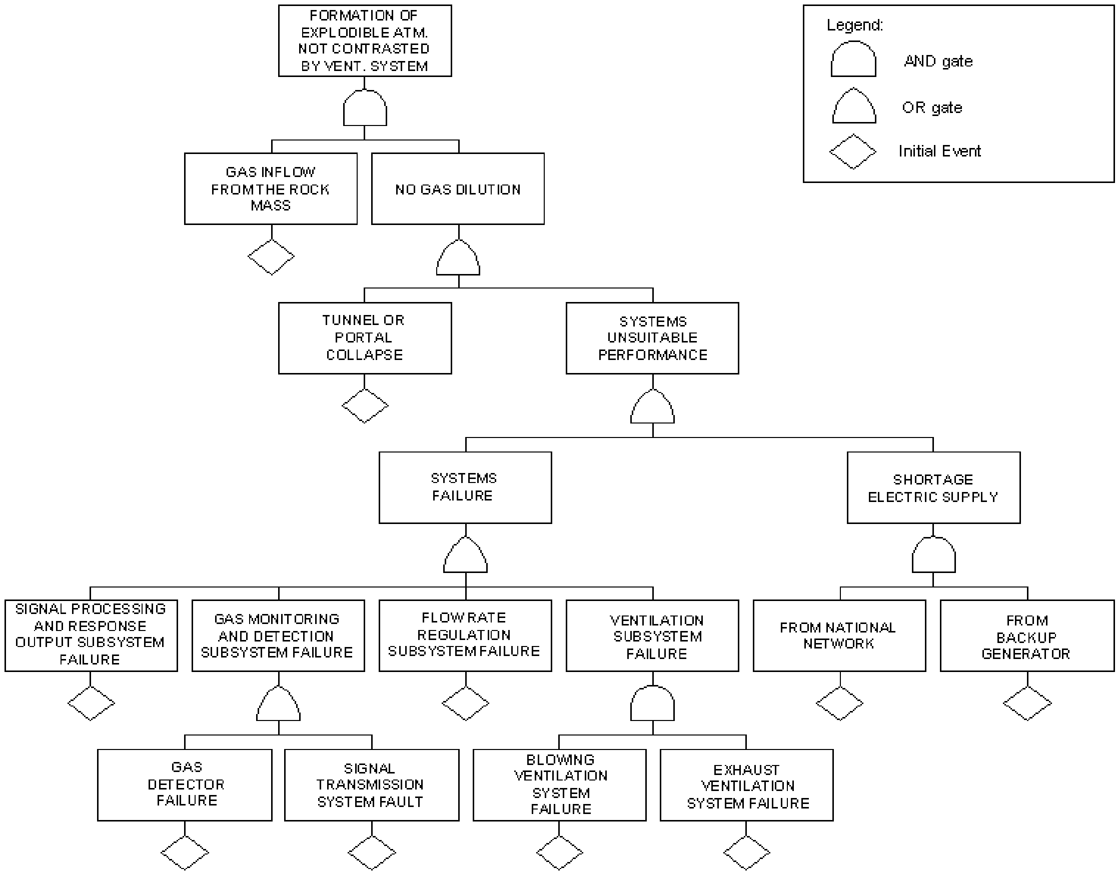

Figure 4: Extract of Fault Tree Analysis for double flow ventilation system

5. Conclusions

Taken for granted the need of very careful Risk Analysis in the case of tunnel driving in rock formations critical for possible firedamp content, the analysis of case histories and the research work confirm the actual possibility to carry out in safety also the tunneling operations in gassy rock conditions.
Only a throughout Risk Analysis based on scientific evidence during the system design phase can lead to an effective decision making on both technologies and procedures, in accordance with the Prevention through Design general approach, worldwide recognized as the only one capable of an effective minimization of the occupational and environmental risks.
For a comprehensive Risk Analysis are necessary the identification, assessment and management of the possible critical scenarios, deviations that may occur, and of the errors which can be made during the execution of the work.
Finally, the paper confirms the satisfactory results of the application, in the aforesaid situations, of a combination of Hazard and Operability Analysis and Fault Tree Analysis.

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