Re-Designing the Ventilation System to Control Unexpected Strata Gases During Tunnel Construction

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ABSTRACT

The paper deals with a mostly unusual incident that took place during the construction of a railway tunnel in the broader area of Athens, Greece. The tunnel, having a length of 3.5 km, was excavated in limestone and brecciated rock formations. When the tunnel reached a length of 1.2 km, personnel complaints and other events raised serious questions with respect to the conditions of the underground environment. Air quality monitoring indicated that there was a surprisingly high concentration of CO\textsubscript{2}, which was attributed to an old uncontrolled landfill located in the vicinity of the tunnel. The paper provides a brief description of the phenomenon, the evaluation of the existing – at that time – ventilation system using both in situ measurements and numerical analysis by means of sophisticated software, as well as the alternative measures proposed to overcome the difficulties during the construction phase.

1. INTRODUCTION

All the underground workings, especially during the construction phase, contain the potential for the presence of air contaminants such as strata gas, blasting fumes, diesel exhausts, drilling dust, etc. Therefore, the ventilation engineer must be concerned with the quantity of the fresh air the ventilation system can deliver, so as to control the quality of the underground environment.

Subsurface “blind” working faces are commonly ventilated by means of the so-called auxiliary ventilation that is fan and duct systems, which either force or exhaust air from the face through a duct. In general, planning an effective ventilation system during the construction phase of a tunnel is not a complex task, assuming that the contaminants and their characteristics are known. Legislation provides specific fresh air quantities per working person and horsepower of operating diesel equipment. Further, in order to control strata gases the amount of the diluting air required can be estimated taking into account the maximum allowable concentration for the contaminant, the rate at which the contaminant flows into the underground work and the concentration of the contaminant in the incoming air.

Based on the required quantity of fresh air and the characteristics of the duct (diameter, friction and shock losses and leakage), an appropriate fan is selected. However, the basic design assumptions of the ventilation system can significantly be altered when unexpected phenomena emerge, which may pose serious threats for the personnel as well as the infrastructure. In these cases, face ventilation problems are exacerbated, and a quite complex situation may arise. This stands for the case presented, in which an unexpected concentration of CO\textsubscript{2} was detected during the construction of a railway tunnel. The rest of the paper details the problem and its main parameters, which were investigated using both in situ measurements and numerical analysis. Further, it describes the alternatives of the ventilation system, developed by means of sophisticated software, in order to confront with the problem.
2. FUNDAMENTALS OF AUXILIARY VENTILATION

In order to design an auxiliary ventilation system, fan and ventilation pipe characteristics should be determined. In tunnels under construction, a blowing-fan system with flexible tubing is the most commonly applied solution. As far as the fan is concerned, the power required depends on the quantity of the air that must be delivered at the working face and the total head-losses, according to the following equation:

\[
N = \frac{P \cdot Q}{1000 \cdot n}
\]

with:  
N = power (kW)  
P = total head-losses (Pa)  
Q = airflow (m\(^3\)/s)  
n = overall efficiency of the fan

In the absence of strata gases, the required inflow is estimated according to the number of persons and the horse-power of internal combustion engine equipment working underground. For example, Greek regulations require 5.66 m\(^3\)/min.person and 2 m\(^3\)/min.HP of fresh air to be supplied. The air to be supplied in the working face for diluting the contaminants is a function of three parameters: (a) the maximum allowable concentration for the contaminants, provided by national regulations, (b) the flowing rate of the contaminant into the underground space and (c) the concentration of the contaminant in the incoming air. In order to be in compliance the following relationship should hold:

\[
Q \geq \frac{(1 - MAC)}{(MAC - B)}
\]

with:  
Q = incoming airflow (m\(^3\)/s)  
MAC = maximum allowable concentration (fraction)  
B = concentration of the contaminant in the incoming air (fraction)

Assuming a leak-free duct system, the determination of frictional pressure drop can be obtained from the Darcy-Weisbach equation for general fluid mechanics, or the Atkinson equation, which is more frequently used in mine ventilation (Hartman et al., 1997):

\[
P = k \cdot \frac{L \cdot O}{A} \cdot u^2
\]

with:  
P = friction loss (Pa)  
k = friction factor (kg/m\(^3\))  
L = airway length (m)  
O = airway perimeter (m)  
A = airway area (m\(^2\))  
u = air velocity (m/s)

This equation can be written as follows, providing the fundamental Square Law relationship:

\[
P = RQ^2
\]

with:  
P = friction loss (Pa)  
R = airway resistance (N.s\(^2\)/m\(^4\))  
Q = airflow (m\(^3\)/s)
The shock losses occurred by changes in the direction or the shape or the size of the duct are commonly expressed in terms of an equivalent length of a straight airway (McElroy, 1935; adopted by Hartman et al., 1997). In order to estimate total head losses for the air power, velocity head, which is lost to the system at discharge should be considered. The equation used to calculate the velocity head takes the form:

\[ P_u = \frac{w u^2}{2g} \]  

with:  
- \( P_u \) = velocity head (Pa)  
- \( u \) = air velocity (m/s)  
- \( w \) = specific weight of air (kg/m³)  
- \( g \) = gravity acceleration (m/s²)

The quantification of leakage from ducts is a complex issue and a number of approaches have been made towards this direction. Howe (1995) suggested the equivalent area hole, expressed in terms of mm²/m² of duct surface per unit pressure differential. Daly (1985) proposed the leakage co-efficient, which considers leakage to be a function of a nominal surface area of duct, a reference static pressure differential and a leakage coefficient with units of m³/s/1000 m²/1000 Pa. Vutukuri and Lama (1986) provide the following equation (termed Woronin equation) for the estimation of leakage, which is applied in this presentation by means of the DUCTSIM software:

\[ R_l = \frac{R_d \times \left( \frac{L}{100} \right)^3}{3 \times \left[ \frac{Q_1}{Q_2} - 1 \right]} \]  

with:  
- \( R_l \) = resistance of leakage paths per 100 m of duct (Ns²/m⁸)  
- \( R_d \) = resistance of duct 100 m (Ns²/m⁸)  
- \( L \) = actual length of duct over which the quantity change (Q₁ – Q₂) is measured (m)

Bearing in mind the above remarks, it becomes evident that leakage results in increased needs of both fan pressure and quantity in order to overcome the leak-free friction and shock losses of the duct and to deliver the required air at the working face.

3. CASE STUDY

3.1 The tunnel and the CO₂ problem

The case study concerns an unusual problem incurred during the construction of “Perama” tunnel (tunnel length: 3.52 km) and its ventilation and escape adit (adit length: 175 m) as well as the ventilation shaft of the emergency chamber (shaft height: 195 m). These underground works, excavated in limestone and brecciated rock masses, are part of the new railway line (total length: 17 km) that will connect Neo Ikonio Port (next to Piraeus Port) with the national railway network.

The construction company designed an auxiliary ventilation system for delivering approximately 21.5 m³/s of fresh air at the working face, based on the requirements of Greek legislation. Nevertheless, when the tunnel reached at a distance of 1.2 km from the entrance, the personnel strongly complained of feeling discomfort. These complaints, as well as other events (e.g. a diesel engine suddenly burnout) raised serious questions with respect to the conditions of the underground environment.

Air quality monitoring indicated that there was a surprisingly high concentration of CO₂. Detection of CO₂ concentration took place under various conditions (different hours of the day, with and without
mechanical ventilation, etc.) and concentration levels reached even up to 11% when mechanical ventilation was switched off.

A research project was assigned to the Laboratory of Mining and Environmental Technology of the National Technical University of Athens to study the phenomenon. Based on the field studies, it was found that the gas was flowing into the underground work from a 400 m-long zone at a distance between 900 – 1300 m from the entrance. Field measurements and theoretical models were used and the flow rate of CO\(_2\) was estimated at 0.6 – 0.9 m\(^3\)/s.

Given that there were no signs of rock strata gas formation, a thorough investigation in the area identified an old uncontrolled landfill, abandoned and covered with soil, located in the vicinity of the tunnel (at a distance of 500 m), as the most probable source of CO\(_2\), for the following reasons:

- It is well known that municipal landfills produce biogas, comprised primarily of CH\(_4\) and CO\(_2\), due to the anaerobic digestion of organic matter. Taking into account the quantity and the composition of the municipal waste disposed to the landfill, CO\(_2\) volume was estimated at 200,000,000 m\(^3\) to 1,000,000,000 m\(^3\) by means of mathematical models. It is noted that the biogas drainage system of the landfill was not in operation.
- The landfill and the tunnel sit in the same rock formation, that is a limestone characterized by carsted conditions. Thus, given also the specific weight of CO\(_2\) and the elevation difference between the landfill and the tunnel (the tunnel is at lower altitude), it is possible that the gas flows through the carst system to the tunnel.

### 3.2 Description of the existing ventilation system

#### 3.2.1 Fans and ducts

The ventilation system consisted of 4 fans operating in series. The total length of the duct by the time of the survey was 1500 m. More specific, the outline of the ventilation system was, as follows:

- At the entrance of the tunnel there was a 2x65 kW twin fan connected with a duct of D = 1.4 m (where D = diameter).
- At a distance of 750 m from the entrance, there was a second fan of 30 kW. The duct’s diameter, right after the fan, was reduced to 1.25 m.
- At a distance of 975 m from the entrance, there was a third 2x11 kW twin fan in operation with D=0.8 m. The diameter of the duct was 1.25 m, but it was reduced to 0.8 m before and after the fan.
- The last fan, with 30 kW power, was placed at a distance of 1,265 m from the entrance. The duct’s diameter from this point till the working face was 1.25 m.

#### 3.2.2 Simulation of the existing ventilation system under normal conditions

The simulation of the ventilation system was carried out by means of the sophisticated software DUCTSIM of the Mine Ventilation Services Engineering, Inc. (a detailed analysis is provided by Duckworth & Lowndes, 2003). The software addresses the problem of leakage from the ducts using the Hardy Cross and the Series Parallel algorithms, which allow for more complex fan and duct configurations (e.g. operation of fans in series, changes in the size and the condition of the duct, etc.). Following the characteristics of the system under investigation from in situ measurements, the ventilation model was constructed. The value of the friction factor was set to 0.004 kg/m\(^3\). For the resistance of leakage paths two different values were considered, namely 15,000 Ns\(^2\)/m\(^8\) for the first 750 m and 10,000 Ns\(^2\)/m\(^8\) for the rest of the duct. Further, shock losses coefficients were appropriately selected. The results of the simulation were, as follows:

- The total resistance of the airways is estimated at 12.8 Ns\(^2\)/m\(^8\)
- The quantity of the air delivered at the working face is 21.5 m\(^3\)/s
- The quantity of the air supplied at the entrance is 26.3 m\(^3\)/s
- The fan characteristics, namely pressure, air quantity and power, are given in Table1 and are graphically represented in Figure 1.
Table 1. Fan simulation results.

<table>
<thead>
<tr>
<th>Distance from the entrance</th>
<th>Q (m$^3$/s)</th>
<th>$H_{\text{total}}$ (Pa)</th>
<th>N (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>26.3</td>
<td>3600</td>
<td>94.8</td>
</tr>
<tr>
<td>750</td>
<td>23.4</td>
<td>950</td>
<td>22.3</td>
</tr>
<tr>
<td>975</td>
<td>22.5</td>
<td>700</td>
<td>15.7</td>
</tr>
<tr>
<td>1265</td>
<td>21.8</td>
<td>950</td>
<td>20.7</td>
</tr>
</tbody>
</table>

Fig. 1. Graphical representation of the fan/duct system (flow and pressure profile).

3.2.3 Effect of CO$_2$ on the ventilation design

On a legitimate basis, the air quantity at the working face under normal conditions (e.g. equipment and personnel working underground) should be 21.4 m$^3$/s. Thus, the existing system was adequate. Nevertheless, field measurements carried out at the end of the duct and at several sections of the tunnel, proved that the quantity of the air ranged between 9.5 – 14.5 m$^3$/s.

The reduced air supply was attributed mainly to the presence of CO$_2$ gas, through the following mechanisms:

- The CO$_2$ gas is 1.5 times as heavy as the air. This affects the estimated friction losses and, in this specific case, it creates a natural ventilation effect, which acts against the mechanical ventilation system.
- The resistance of the ventilation circuit is also affected by the CO$_2$ inflow. In the entrance zone mentioned, the CO$_2$ concentration received its maximum value and the air velocity dropped significantly.

However, the most important effect of CO$_2$ presence in the working place is the need to provide an additional amount of air for the dilution of the contaminant to allowable levels. Based on the estimated inflow rate of the gas, it was calculated that the inflow rate of the incoming air should be increased by 50%, that is 30 m$^3$/s.

3.3 Proposed solutions

Taking into consideration the characteristics of the project (number and geometry of underground openings, scheduling of completion time, etc.) and the phenomenon, three alternatives were
considered to supply 30 m$^3$/s of air at the working face. Based on the simulation of the alternative ventilation systems, the following figures derived:

- **Alternative 1:** Installation of a new 160 kW auxiliary fan and replacement of the existing duct with a new 1.6 m diameter duct, for the total length of 1500 m.
- **Alternative 2:** Abolition of the existing auxiliary ventilation system and installation of a new 350 kW blower fan at the ventilation shaft. It is noted that the air power required is significant due to the high friction losses, given that the shaft’s diameter is only 1 m.
- **Alternative 3:** Installation of a new 30 kW blower fan at the ventilation shaft, which will operate in parallel with the existing auxiliary ventilation system and it will provide the additional 10 m$^3$/s needed.

According to rough estimates of the total cost (i.e. capital and operating costs), the Alternative 3 proved to be superior. Further, bearing in mind that CO$_2$ presence was quite sensitive to the difference between the underground space head and the atmospheric pressure, it is expected that the new fan will also reduce the CO$_2$ inflow rate.

### 4. CONCLUDING REMARKS

In general, designing an auxiliary ventilation system to fulfill the ventilation needs during the construction of a tunnel is not a complex task, as long as rational assumptions (i.e. for the friction factor and the leakage resistance) are made and ducts are well maintained. However, the situation may become quite complicated, if unexpected incidents take place.

In the case studied, an unpredicted factor, namely the CO$_2$ inflow, upset the designed ventilation system and resulted in poor safety conditions. In order to overcome the problem, serious modifications should be made that would cost money and time. The treatment of the problem, however, would be much easier and, perhaps, more economic, if the phenomenon was known at the beginning of the project. For example, if the diameter of the shaft increased from 1 m to 1.5 m, the power of the fan in Alternative 2 would be reduced to 30 kW, making clear that from technical and economic point of view prevention is always preferable to treatment.

### REFERENCES