DESIGN OF A VENTILATION SYSTEM IN A TUNNEL BORED WITH A TBM MACHINE IN THE CASE OF METHANE EMISSION FROM A ROCK MASS

Marek Borowski , Klaudia Zwolińska-Glądys, Andrzej Szmuk, Zbigniew Kuczera, Kamil Piech
AGH University of Krakow, PL

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ABSTRACT

Methane emissions from rock masses pose a significant hazard in underground works, leading to delays and, in the worst case, tragic accidents for workers. Therefore, before beginning mining work, it is necessary to properly design and optimize the ventilation system to ensure safety in the tunnel and prevent possible explosions. This paper presents a case of methane emissions observed before the drilling of the road tunnel. Initially, no emissions problem was expected. However, by preparing drainage wells to reduce water pressure in a rock mass, methane outflow was noticed. The presented analysis covers the design of a ventilation and safety system developed for drilling a tunnel along the S-19 expressway in south-eastern Poland. This two-tubed tunnel is being bored using a TBM and is expected to reach a final length of over 2.2 km. In response to the noticed risk, a ventilation and security system was developed, and a simulation of air dispersion and methane concentration distribution was performed. The developed ventilation and security system is intended to enable the tunnel drilling to continue without interruption, even in the event of significant gas inflows.

Keywords: Ventilation system design; Tunnel Boring Machine (TBM); Methane emission mitigation; Worker safety in tunnels; Environmental impact control, Methane explosion risk.

1. INTRODUCTION

Tunnel Boring Machine (TBM) technology has grown in popularity over the past decades due to significant technological advances. This progress enabled higher tunneling rates, larger drilling diameters (up to 17 m), and lower tunneling costs.

As with all underground works, drilling tunnels may be associated with a risk of methane inflow from rock massifs. Mostly, tunneling at shallow depths is not associated with methane emissions. Nevertheless, the possibility of the presence of methane-air mixtures should be analyzed at the initial stage of the project, especially in the case of rock masses with a complex geological structure. Methane emissions can pose a severe hazard and cause delays in work or even tragic accidents. In the case of a methane threat, it is necessary to design and implement an appropriate ventilation system, which allow to obtain safety working condition.

Due to the impossibility of preventing the simultaneous presence of an explosive mixture of methane with air and ignition sources, TBM machines were not used to drill tunnels in gas rock massifs until 2011, except in cases where the methane hazard was underestimated at the design stage, which consequently led to delays and unexpected costs.

In tunneling, the risk of methane explosions has generally been underestimated, and there have been very few attempts to transfer the vast experience gained in underground coal mining to tunneling. Nevertheless, since the beginning of the 20th century, many studies have been carried out on the origin and mechanisms of methane inflow in the field of mining engineering. The knowledge gained from this research has contributed to the methods of preventing methane explosions, improving the forecasting and management of such a threat [1].

Despite limited scientific literature on tunneling in gaseous rock masses [2,3], it should be stated that methane may pose a crucial threat during tunneling. Methane occurs in many rock formations, mainly sedimentary ones. Gas emissions are often stochastic and have a non-uniform distribution [4], which makes it difficult to assess the methane risk through preliminary geological surveys. Inappropriate forecasts of the inflow of methane into the tunnel may result in costly delays and, in the worst case, tragic accidents for workers [4-7]. In paper [6], the authors reviewed the world's catastrophic methane explosions during the construction of tunnels.

The article aims to present the design of a ventilation system when drilling a tunnel using a TBM machine in methane-hazard conditions. The paper focuses on the specific case of methane hazard in the S-19 tunnel, presenting modeling of the ventilation system as a method of minimizing the risk associated with the presence of methane during drilling with a TBM machine. The introduction, methane hazard analysis, and ventilation system design with modeling results constitute the structural elements of the article.

2. METHANE HAZARD IN TUNNELS

2.1. Sources of methane emissions in analyzed tunnel

The rate of methane release from the rock formation is contingent on its permeability and could significantly vary based on the rock type and region of its occurrence. The permeability characteristic is significantly influenced by the rock heterogeneity. Permeability is mainly secondary, related to the degree of fracturing, except compressed sediments characterized by primary permeability. Flysch formations generally have permeability ranging from moderately low (sandstones) to very low (shales/mudstones). In the tectonic area (faults and the cracked part of the rock mass), they are characterized by higher values. Clay shales will have very low permeability due to the dominant clay component.

As mentioned above, this paper presents a case study for drilling tunnel on the road S-19 in Poland. At first, the analysis focused on the identification of the methane emission sources and a preliminary assessment of the hazard level. Based on geological reconstruction, several geological structures were selected along the tunnel route and classified as potential localization of methane accumulation or inflow. Such permeable fragments of the rock mass, surrounded by impermeable rocks, may enable gas accumulation and migration due to morphological conditions related to the presence of anticlines and faults. The literature survey also showed that methane can be emitted by geological discontinuities, as shown in Figure 1.

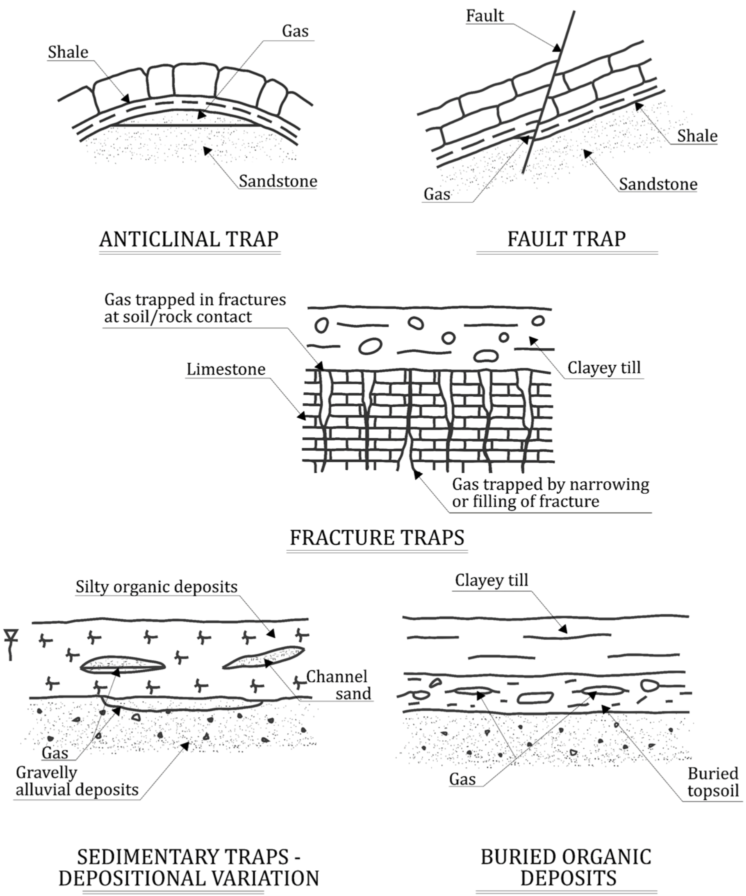

Figure 1: Structural and sedimentary gas traps/deposits. Based on [8].

Based on the analysis of previous observations and the occurrence of methane during the drainage of the S-19 tunnel surrounding area, as well as using tests of chemical origin, it should be concluded that we are dealing with a complex situation due to the occurrence and origin of methane. From the analysis of the structural conditions, it can be concluded that we are dealing with an anticline trap and gas supply related to a fault. As for the origin of the gas, both thermogenic and biogenic gas were found. It may indicate an inflow of gas from deeper layers, e.g., along a fault, and the methane from gas traps in organic sediments. Nevertheless, it should be emphasized that the crucial issue may be connected with the inflow from deeper layers, which was confirmed in the drainage holes. As presented above, determining methane emissions may cause difficulties in predicting the methane flow into the tunnel, which poses a challenge in solving the ventilation method and securing the TBM machine.

2.2. Determination of critical zones in the tunnel and approximate methane inflow

Based on drainage tests, areas associated with the occurrence of methane were identified (Fig. 2). The drawing shows in green the localization of drainage points where no methane was observed, and in red, where methane was noticed. An ellipse frames the zone of expected intense methane inflow into the tunnel during drilling. In the highlighted part, methane hazards may become apparent during TBM drilling. Based on the results of water pumping tests, attempts were made to estimate the methane inflow.

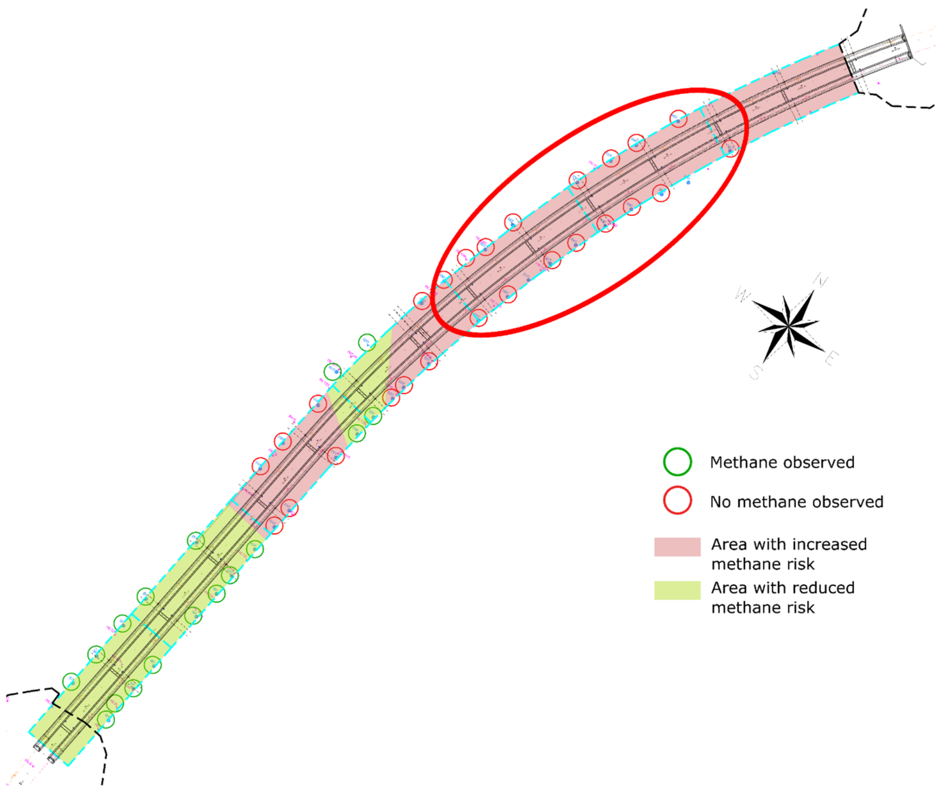

Figure 2: Distribution of methane zones in drainage wells

Figure 3 shows the methane inflow in the drainage wells. In the case of conventional deposits, methane emissions, as on the right side of Figure 3, could be expected. The preliminary analysis indicates that, to some extent, the study case could be characterized by this type of methane inflow. Therefore, if the confirmed water inflow is a maximum of 10 m^3/h (0.166 m^3/min) to a single well, several times higher methane inflow could be expected in extreme conditions. Assuming up to 10 drainage holes in use during tunnel drilling, and each hole may receive 0.5 m^3/min, the maximum methane emission into the tunnel may be 5.0 m^3/min. A safety factor of 2 was adopted, so for the calculations of the ventilation system, it was assumed that methane emission into the tunnel would be 10 m^3/min.

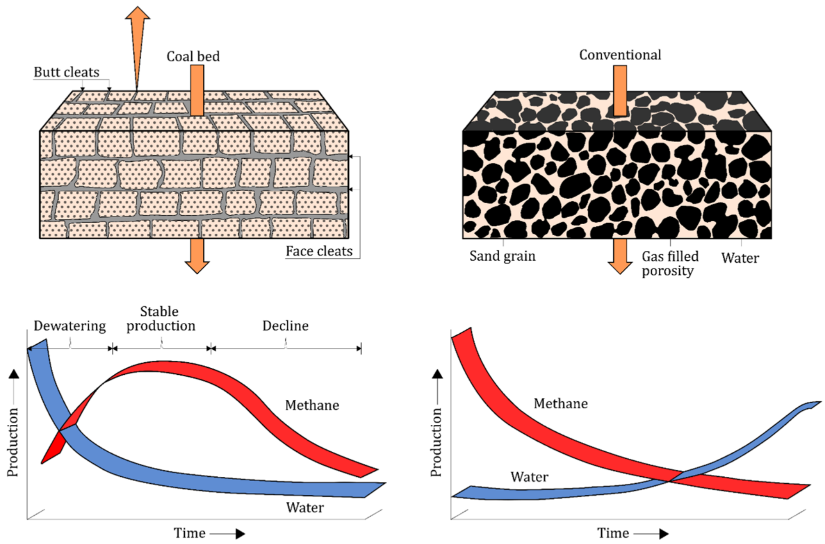

Figure 3: Characteristics of the methane inflow in the drainage well [9]

3. MODELING THE VENTILATION SYSTEM

3.1. Selection of the type of ventilation system for the tunnel

Due to the structure of the TBM, it was proposed to adapt ventilation to two drilling phases (Fig. 4):

- Stage 1 - After starting the TBM machine and drilling a section covering the length of the TBM machine. Then, the ventilation system installed on the TBM machine will work.
- Stage 2 - After entering the TBM machine into the bored tunnel. The main ventilation will be activated with a fan located in the tunnel portal area.

Considering the operation of the TBM machine in methane hazard conditions, it will be necessary to equip the machine with protection consistent with ATEX requirements. Since it is impossible to adapt the entire TBM machine to requirements, only the safety systems of the machine will be ATEX-compliant and fully protected to maintain "vital" functions.

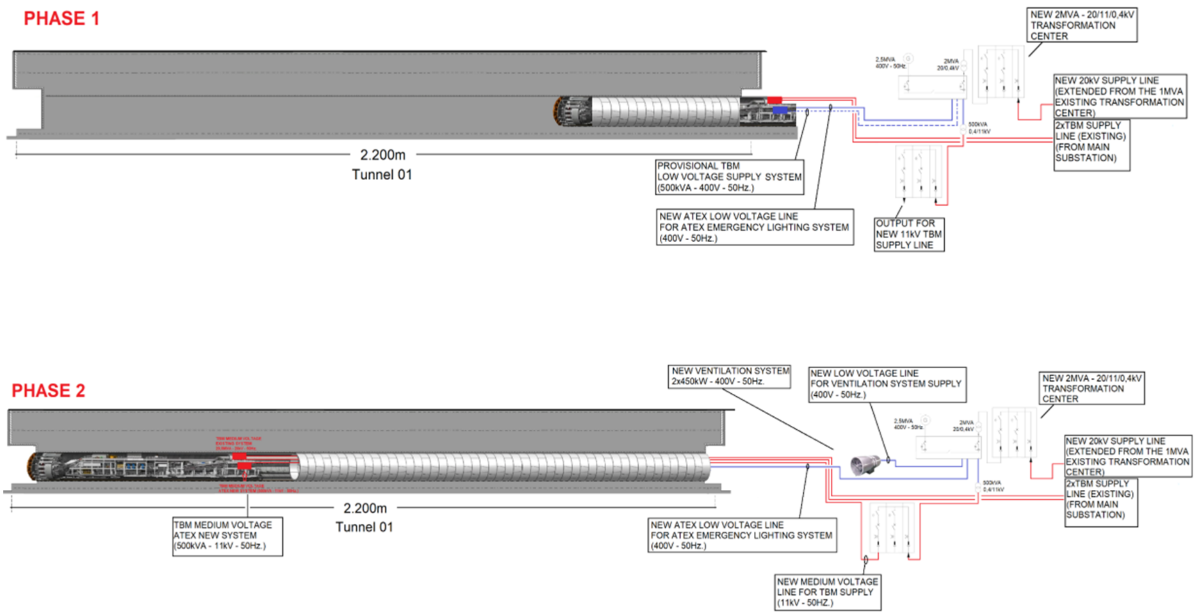

Figure 4: Tunnel drilling phases with ventilation adjustment [10]

Considering the methane hazard, it is necessary to use forced ventilation due to the greater range of the air stream flowing from the duct. It is crucial to ensure appropriate airflow turbulence in the red zone marked in Figure 5.

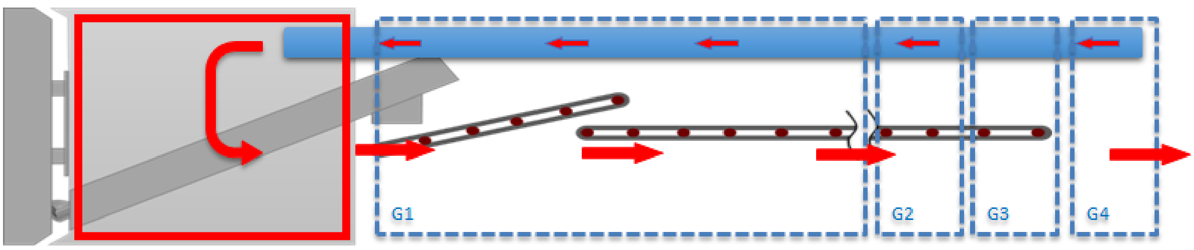

Figure 5 : TBM machine ventilation concept [10]

To calculate the air velocity distribution and volume rate in the tunnel, a 1D ventilation model for the maximum length, based on the tunnel equipment design, was prepared. For this purpose, available engineering software was used that allows for flow analysis of ventilation networks, including mines and tunnels [11]. Calculations were carried out for a single TBM bored tunnel with a length of 2155 m. The model consists of sidings (tunnel sections and a duct between nodes - points) with transverse dimensions and unit resistances appropriate for the designed tunnel in the drilling phase and a pressure duct divided into segments with a diameter of 2500 mm (2070 m) – the principal ventilation and of 1800 mm (85 m) – TBM machine ventilation.

The duct outlet should not be at a distance greater than 20 m from the TBM machine disc. The view of the model is shown in Figure 6. An axial fan is connected 50 m from the tunnel portal inlet (Figure 7) to ensure no recirculation of the exhaust air. from the tunnel.

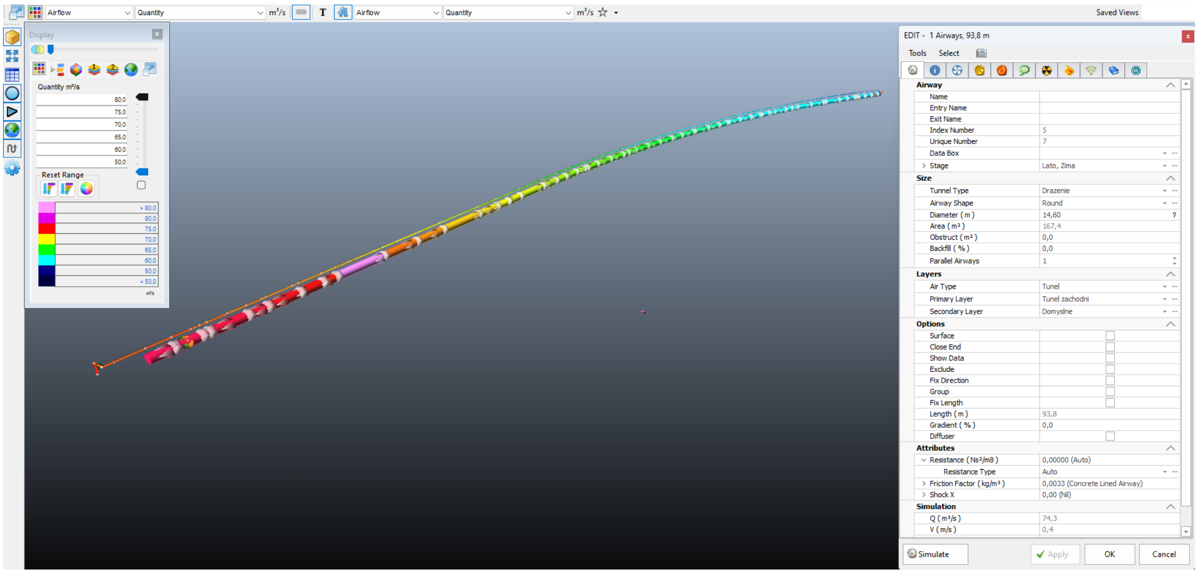

Figure 6: View of the tunnel model and the supply duct

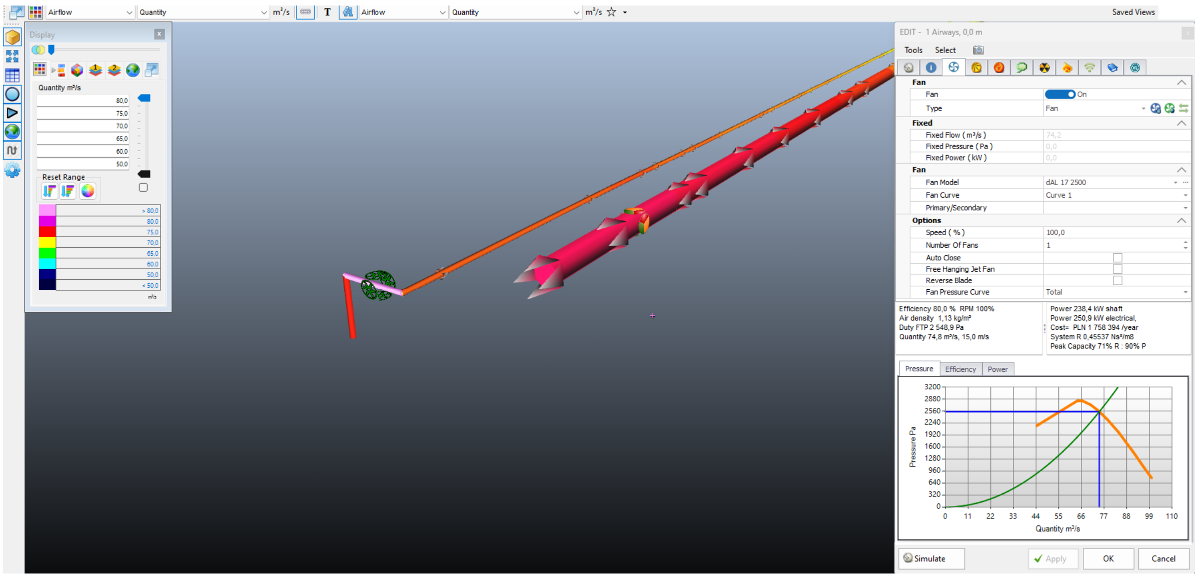

Figure 7: Location of the fan and its characteristics in front of the tunnel inlet

3.2. Results of modeling for the tunnel with the designed ventilation system

The airflow of 53.5 m^3/s is supplied to the TBM machine disc via the air duct with an efficiency of 71% (due to leakage along the duct). Distribution of the changes in airflow rate (Fig. 8) and its velocity (Fig. 9) were shown along the length of the tunnel. On the horizontal axis, the point of 0.0 m corresponds to the disc of the TBM machine. As you move away from the heading, the amount of air increases along the length of the tunnel, which results from the air duct leakage and is a phenomenon resulting from the nature of the solution. According to the legal regulation, the provided airflow ensures a minimum air velocity of 0.3 m/s to mitigate the methane hazard.

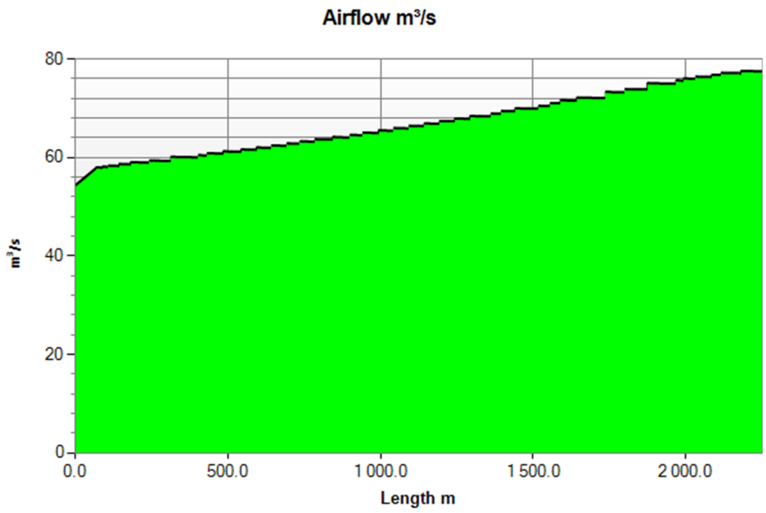

Figure 8: Distribution of the airflow rate (m^3/s) in the tunnel cross-section with increasing distance from the heading/disc of the TBM

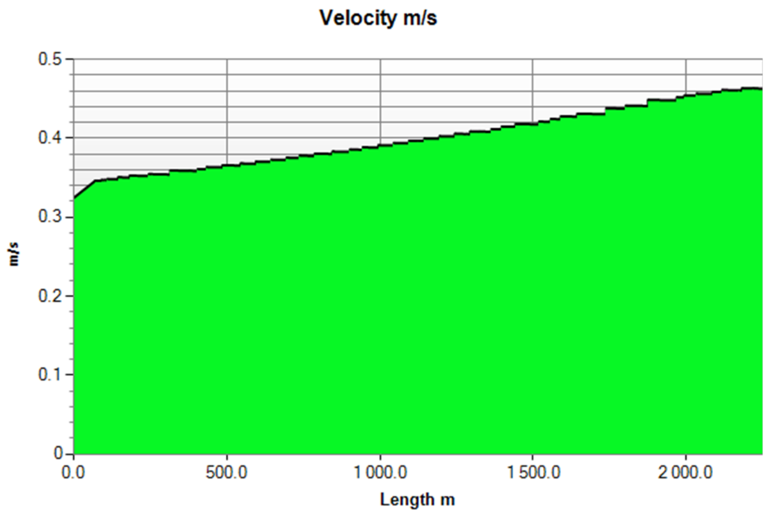

Figure 9: Distribution of the air velocity (m/s) in the tunnel cross-section with increasing distance from the heading/disc of the TBM

Based on the analysis from the previous chapter, the methane flow released into the tunnel was acquired to be 10 m^3/min of pure gas. The inflow of methane into the tunnel was assumed to be linear in the roof part (25% of the total outflow) and the bottom part (25% of the total outflow) of the heading, as well as the point inflow of methane (injector) at the outlet from the screw conveyor (50% of the total outflow). The distribution of methane concentration is shown in Figure 10. The analysis shows that with the given amounts of air, the permissible methane concentration of 0.5% will not be exceeded. If the concentration does not exceed

0.5%, the TBM is not required to comply with ATEX requirements but only selected elements of the so-called function support of the TBM. An average concentration of 0.3% is observed at the front of the tunnel heading/shield and 0.2% at the tunnel outlet. Due to possible threats, it is necessary to implement appropriate precautions among additional security measures. Devices and systems such as submersible pumps for emergency drainage, sewage pumps, the fan in the gantry, the vacuum pump of the erector and the segment lift, the lighting and emergency lighting, as well as the gas monitoring system and the evacuation alarm system should be classified at least in category M2 (high level of protection, EU Directive 94/9/EC on equipment and protective systems intended for use in potentially explosive atmospheres). The remaining devices should be classified in category II G2.

In conclusion, the designed ventilation system effectively controls airflow, maintains permissible methane concentrations, and ensures compliance with safety regulations. While ATEX safeguards might not be mandatory for the entire TBM, the implementation of specific security measures is advised to address potential threats and enhance overall safety in the tunneling process.

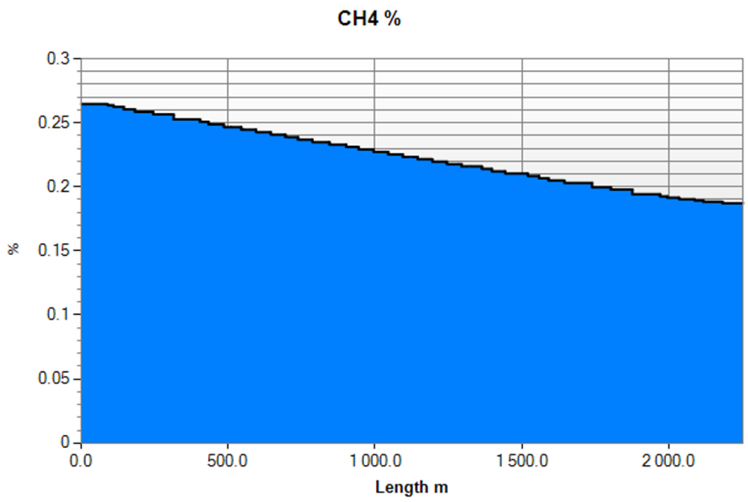

Figure 10: Distribution of methane concentration (%) along the airflow path through a bored tunnel.

4. CONCLUSION

Tunnel drilling in gaseous rock masses carries a severe risk of methane ignition/explosion/explosion, which requires monitoring, preventive measures, and appropriate safeguards. The main goal of the design and ventilation modeling during TBM drilling in methane hazard conditions is to ensure the safety, efficiency, and controlled operation of the TBM machine in the tunnel. The internal environment control in the tunnel is to enable continuous operation of the TBM, thanks to which tunnel drilling can be carried out efficiently, and delays and costs associated with downtime will be minimized.

Based on the analysis of previous observations and the occurrence of methane during the drainage of the surrounding area and using tests of chemical origin, it should be concluded that we are dealing with a complicated situation. From the analysis of the structural conditions, it can be concluded that we are dealing with an anticline trap and gas supply related to a fault. As for the origin of the gas, both thermogenic and biogenic gas were found. It may indicate that there is an inflow of gas from deeper layers, as well as from gas traps in organic sediments. Based on test water pumping, it was assumed that methane emissions into the tunnel would be 10 m^3/min.

For methane hazard reasons, it is necessary to use forced ventilation due to the greater range of the air stream flowing from the duct in the area of the TBM shield. To determine air velocity and flow rate distribution, a 1D ventilation model for the maximum length was prepared. Calculations were carried out for a single TBM bored tunnel with a length of 2155 m. The air stream fed to the front of the tunnel behind the TBM machine disc ensures that the minimum air velocity is maintained along the entire length of the tunnel. The analysis of the methane concentration distribution shows that the value of 0.5% will not be exceeded at the given amounts of air (the stream supplied to the air duct is 75.3 m3/s). An average concentration of 0.3% is observed at the front of the tunnel face/shield and 0.2% at the tunnel outlet. For safety reasons, the TBM machine should be equipped with methane measurement sensors.

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