THE AIR-FLOW STRUCTURE AND GAS DISPERSION BEHAVIOR IN GAS TUNNEL CONSTRUCTION THROUGH BENCH CUT METHOD

by

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The inability to accurately predict the in rush of gas increases the fear of field workers security and unnecessary investments in tunnel ventilation. In this study, a 3-D numerical model was established to investigate the air-flow structure and gas diffusion characteristics of a gas tunnel during construction. The result showed that the flow inside the bottom bench mainly came from the re-circulation zone of the upper bench. Mutation in the tunnel section due to bottom bench excavation would cause the formation of some air circulation in the bottom bench. The circulation air in the bottom bench came from the re-circulation zone of the upper bench, while the air-flow in the considered zone was a polluted air. Based on the obtained results, there was no accumulation of CH_4 inside the bottom bench. Nevertheless, gas gushing will still appear during the construction of the bottom bench surface, which can possibly lead to gas disaster. This study aims to provide some guidance for tunnel engineers on safety monitoring systems.

Key words: *air-flow, bottom bench, gas tunnel*

Introduction

China's tunnel construction has realized a tremendous achievement in terms of both tunnel number and tunnel mileage. As the number and length increase, there are growing occupational disease patients. During the construction phase, workers may be exposed to various toxic and harmful gases and dusts. The ventilation system is important to ensure safety during tunnel construction. The commonly used construction methods include full-section methods, bench cut methods, and sub-construction methods. Among these methods, the bench cut method is the most popular one. Bench cut method will lead up to the creation of two faces namely the upper bench face and the bottom bench face, and both of them will be subjected to toxic and harmful gases as well as the generated dust. There is only one air supply vent for the multi-face construction and it has not been verified whether the ventilation pattern can meet the requirements for all faces.

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During the construction phase, tunnel is a half closed space, where ventilation is very difficult to realize with the presence of a variety of toxic and harmful gases and dust [1-3]. The role of tunnel ventilation is recognized as *Security Guard* in tunnel construction [4]. A large number of scholars have conducted many researches on air-flow structure for ventilation in tunnel during construction using mathematical and computational modelling. The changes of tunnel air-flow under the influence of different structures was studied in [5, 6]. The diffusion operation rules of various pollutants generated by tunnel construction were also studied using numerical simulation software in [7, 8]. The numerical simulation methods to study the ventilation of operating tunnels were employed in [9]. Most of these studies focused on the ventilation of the heading face as well as the flow field and distribution of pollutant concentration. However, there are few research on air quality inside the bottom bench as well as the influence of the upper bench flow field on the flow in the bottom bench.

The aim of this study is to determine the flow field and the distribution of hazardous gas in the bottom bench of the tunnel. In the study, the hazardous gas CH_4 that is usually encountered in practice were taken into consideration, and FLUENT software was used to simulate the flow structure, migration and diffusion of toxic and harmful gases inside the bottom bench of the tunnel during construction. The results of these calculations provide a reference for an optimal lay-out of monitoring sensors as well as a reliable guidance for the workers on the construction field to avoid dangerous areas.

Numerical model and calculation

Methodology

In the calculation of the diffusion characteristics of CH_4 in the tunnel (given that CH_4 does not burn or explode), not only mass conservation and momentum conservation are required, but species mass-conservation is also required. For component *S*, the species mass-conservation equation can be written:

$$\frac{\partial\left(\rho c_s\right)}{\partial t}+\nabla\left(\rho\vec{u}c_s\right)=\nabla[D_s\nabla(\rho c_s)]+S_s \tag{1}$$

where c_s is the volume concentration of component *S*, ρ – the mass concentration of the component S_s, and D_s – the diffusion coefficient of the component *S*.

The four items from left to right in eq. (1) represent time change rate, convection item, diffusion term and response term, respectively. The mass conservation equation of a component is basically a concentration transfer equation. When a certain pollutant flows in the air, the transmitting procedure includes convection and diffusion. The concentration of the pollutant changes with time and space.

Model description

In this paper, the Huayingshan tunnel on the Yubei-Guangan Expressway was taken as the research object. Yu-guang Expressway, with a total length of 98 kilometers, was constructed under the Chongqing's new-kilometer expressway project initiative. The bench cut method was used for the construction of the Huayingshan Tunnel. This study focuses on the air-flow and CH_4 dispersion near the bottom bench. There were four sections of different sizes existing in the tunnel during the construction phase. Therefore, the tunnel could be divided into sections as upper section, full section, inflected arch and bottom bench complete section, and finally secondary lining complete section. The four tunnel sections are shown in fig. 1. The establishment of a 3-D model was based on the size of the Huayingshan tunnel. The length of the tunnel model

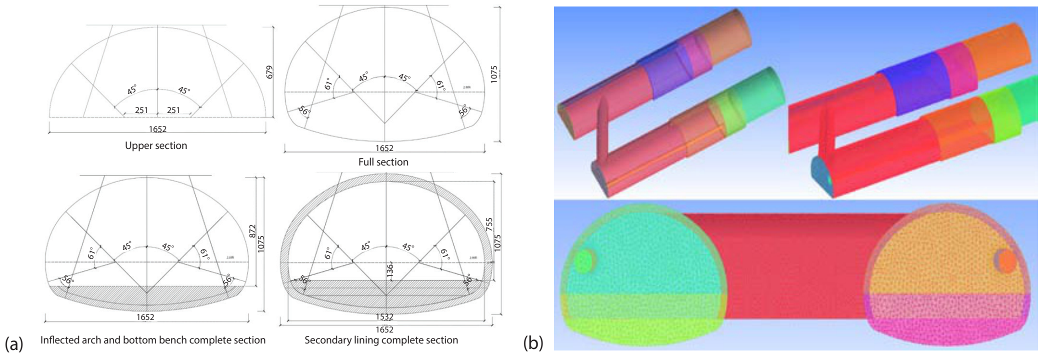

Figure 1. Tunnel sections and dimensions and mesh

is 90 m, the upper section is 20 m, the full section is 10 m, the inflected arch and bottom bench complete section is 20 m, and the secondary lining complete section is 40 m. The duct diameter is 1.8 m and the outlet of duct is 30 m away from the face. The left and right sides of the tunnel are 30 m distant one from another, and the angle between the transverse gallery and the tunnel is 60°. The tunnel model and mesh are shown in fig. 1.

Results and discussion

Air-flow in the bottom bench

Based on previous settings, the face plane is set on the wall when analyzing the air-flow structure. Fresh air enters the tunnel from the air duct and then moves to the tunnel portal. Figure 2(a) shows the streamline of a plane. The vertical distance between such plane and upper bench is 1.6 m, which is exactly equal to the distance from the construction workers' nose to the ground.

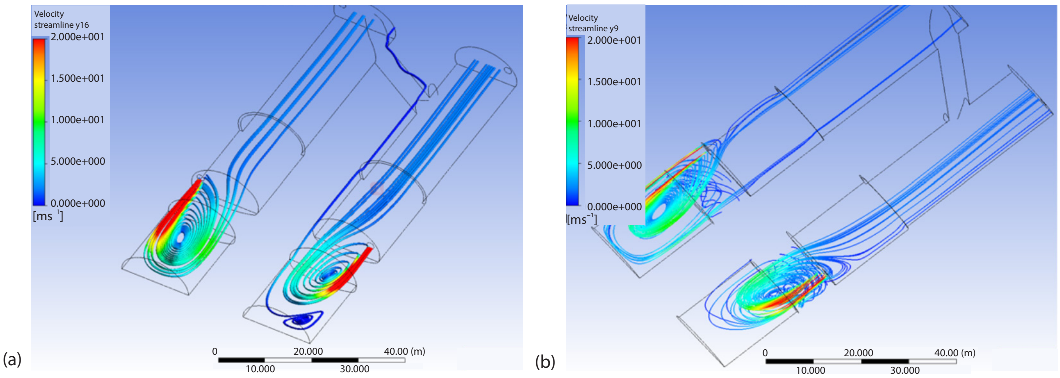

Figure 2. Streamline in the 1.6 m plane (*for color image see journal web site*)

As a result, the tunnel air-flow can be divided into three zones namely the jet flow zone, the eddy zone and the re-circulation zone, as shown in fig. 2(a). Figure 2(b) shows the streamline in the whole tunnel and the three zones can be clearly seen. Part of the air-flow in the jet flow zone comes from the air duct while the other part is obtained by suction effect. A part of the air-flow in the re-circulation zone is sucked by the jet flow zone, while the other part is discharged along the excavation tunnel. The eddy zone is formed due to space limitations and the suction effect.

The section of the tunnel after the construction of the bottom bench is significantly larger than that during the construction of the upper bench. Due to the abrupt change of the section, the air-flow structure will be affected. Figure 3 shows the streamline in the bottom bench. As it can be seen, sudden changes of the section lead to the formation of the eddy zone in the bottom bench. Moreover, the eddy zone in the bottom bench starts at the re-circulation zone of the upper bench. The re-circulation zone in the upper bench is filled with polluted air after cleaning the face. The bottom bench also goes through the same construction procedures as the upper bench, which are blasting, slagging and support. Therefore, the same pollutants like toxic and harmful gas and dust will appear. Thus, this type of ventilation will cause more damages to workers inside the bottom bench.

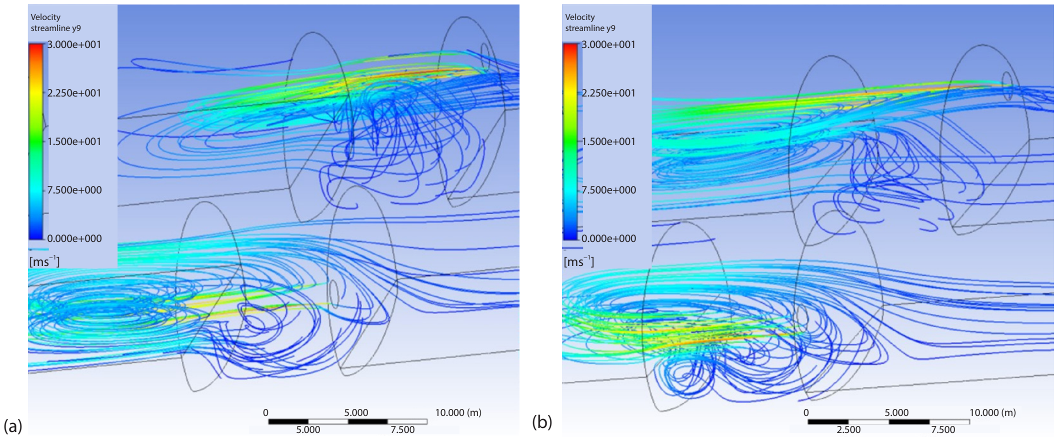

Figure 3. Streamline in the bottom bench (*for color image see journal web site*)

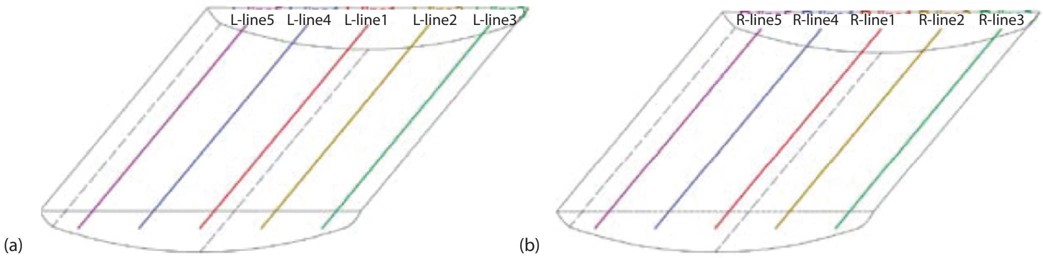

Figure 4. the location of each line

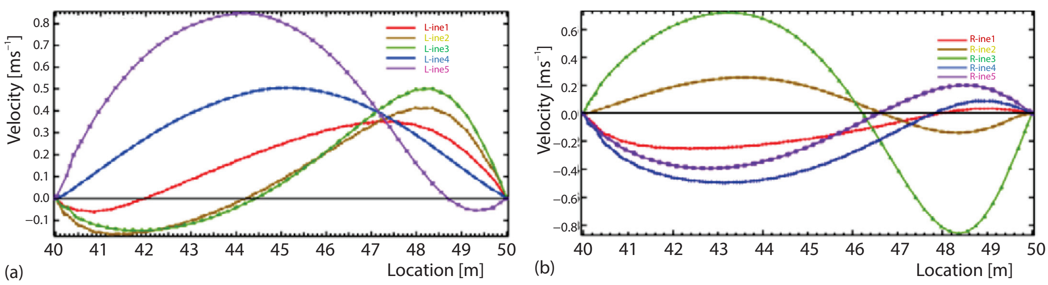

Figure 5. Velocity-line curve at bottom bench

In order to better observe the air velocity in the bottom bench, 10 lines were set up in the bottom bench of the double tunnel. Among them, 5 lines were distributed in the left tunnel, 1 was placed at the center of the bottom bench, and the remaining 4 others were disposed at 3 m and 6 m on both sides of the centerline. The locations of lines are shown in fig. 4. Figure 5 gives the velocities on each line. The positive air velocity in this figure indicates that the airflows from the face to the tunnel portal. According to figs. 3 and 5, it can be found that the air in the bottom bench comes from the re-circulation zone and the eddy zone.

Distribution of gas

In order to analyze the distribution of harmful gases in tunnels on the bottom bench, the source of harmful gas on the face was determined from calculation. During the construction period of the huayingshan tunnel, the absolute gas emission at the site was measured to be 5.624 m^3/min. Therefore, the face was set as the mass entrance with the value of 0.0723 kg/s. The gas concentration in the key section, shown in fig. 6(a), was monitored. The observation of the concentration change of the gas in the bottom bench was facilitated by selecting some key faces near the bottom bench.

Figure 6(b) shows the change of CH_4 concentration at key sections along with the time. As it can be seen from the figure, the CH_4 concentration on the face increases rapidly because the air from the fan has not yet reached the face at the very beginning of the ventilation. When the fresh air reaches the face, the CH_4 of the face will fall rapidly. The CH_4 concentrations on the other four sections grow slowly with time. In the later period of ventilation, the CH^4 concentration in key sections gradually tends to be stable. Besides, there is no significant difference in CH_4 concentration among Z_1, Z_2, Z_3, and Z_4. Interestingly, the CH_4 concentration of Z_1 and Z_2 which are located close to the face is significantly higher than the CH_4 concentration of Z_3 and Z_4 which locate relatively farther from the face. Throughout the ventilation period, the CH_4 concentrations on Z_1 and Z_2 are continuously larger than those on Z_3 and Z_4, and that is particularly significant during the late period of ventilation. This indicates that the CH_4 concentration is effectively diluted with the increase of return air distance, *i. e.* the CH_4 concentration will decrease with the increase of the distance from the face.

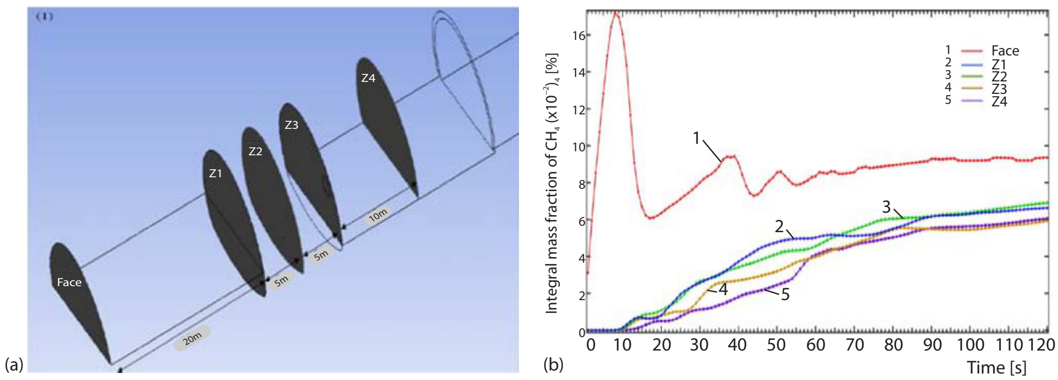

Figure 6. The position of the key section (*for color image see journal web site*)

The distribution of CH_4 on key sections is shown in fig. 7. After CH_4 overflows from the face, it is only present at the top in the beginning of the calculation, because the CH_4 density is lower than air. With the continuous increase of CH_4 emission, the CH_4 concentration in the tunnel also keeps increasing. The CH_4 spreads from the vault to the entire section. At t = 120 seconds, the high concentration of CH_4 in the tunnel mainly exists at the top of the bottom bench. The *CH_4 package* at the top of the bottom bench is very dangerous for welding and other work.

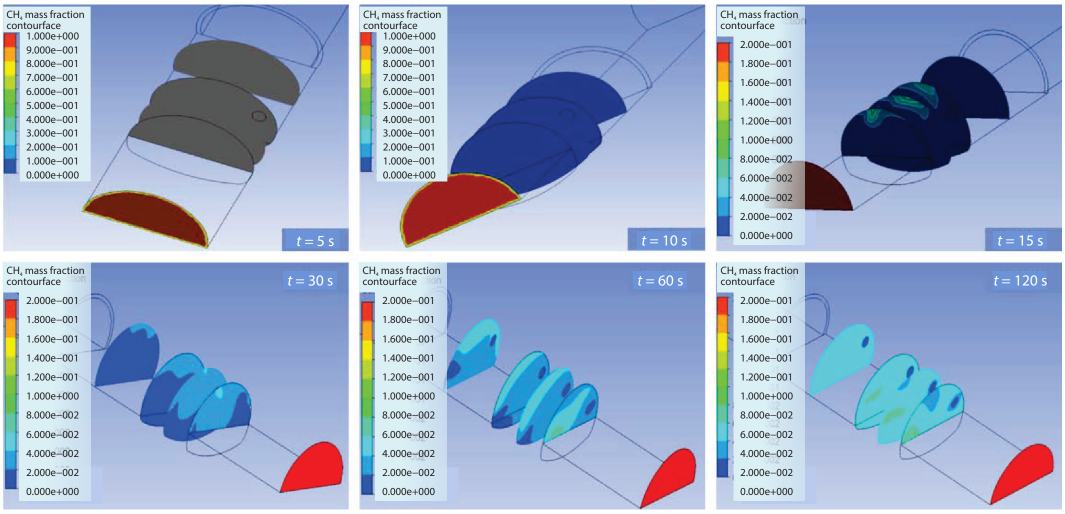

Figure 7. The CH_4 distribution

Figure 8 shows the cloud chart of CH_4 concentration at the Z_2 section. It can be clearly seen that CH_4 spreads from the vault to the entire section. The location where the CH_4 concentration is high is always the side away from the duct. The high-concentration CH_4 region is not exclusively located at the top, but in the re-circulation zone as well. As it can be seen from fig. 9, the CH_4 in the plane also flows into the re-circulation zone and the eddy zone and then diffuses out of the tunnel. However, there is no significant accumulation of CH_4 in the bottom bench.

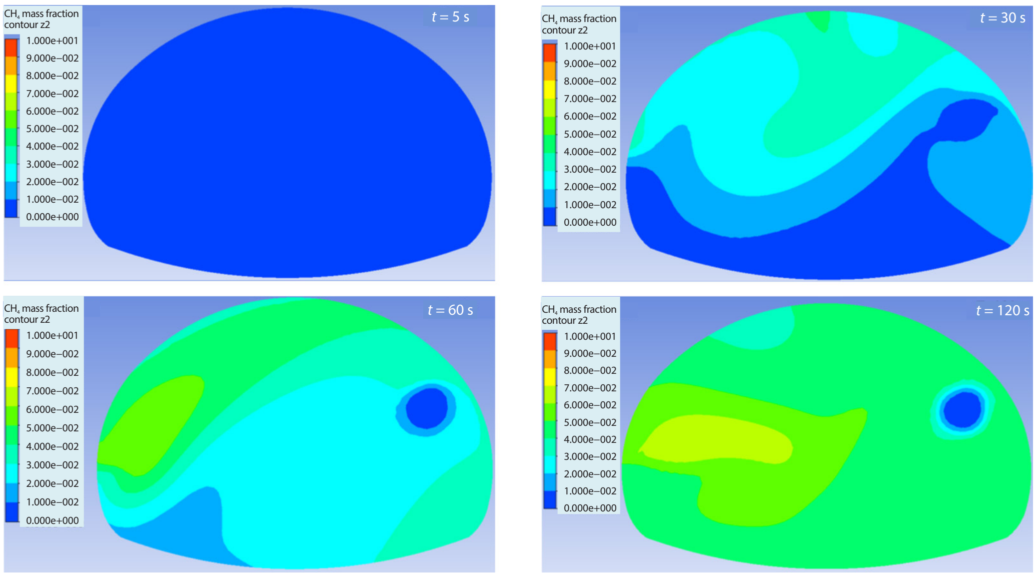

Figure 8. The CH_4 concentration distribution at Z_2 section

Discussion

Once toxic and harmful gases enter the eddy zone, the gas will circulate within that zone. As shown in fig. 9, CH_4 forms an equivalent area in the eddy zone, and the CH_4 concentration there is not greater than that in the re-circulation area. This shows that most of the CH_4 can enter into the re-circulation zone and pull out from tunnel when the CH_4 reaches a certain amount. From T = 30 s to T = 60 s in fig. 9, the CH_4 concentration in the eddy zone does not change much, but the area is increasing. This change is a good indication of the sealing effect in the eddy zone. The sealing effect not only can inhibit the outside air from entering in but also prevents the closed interior air from discharging. It is extremely easy for high density harmful gases and dusts to accumulate in the eddy zone. Therefore, the atmospheric environment in the eddy zone should be given a high attention.

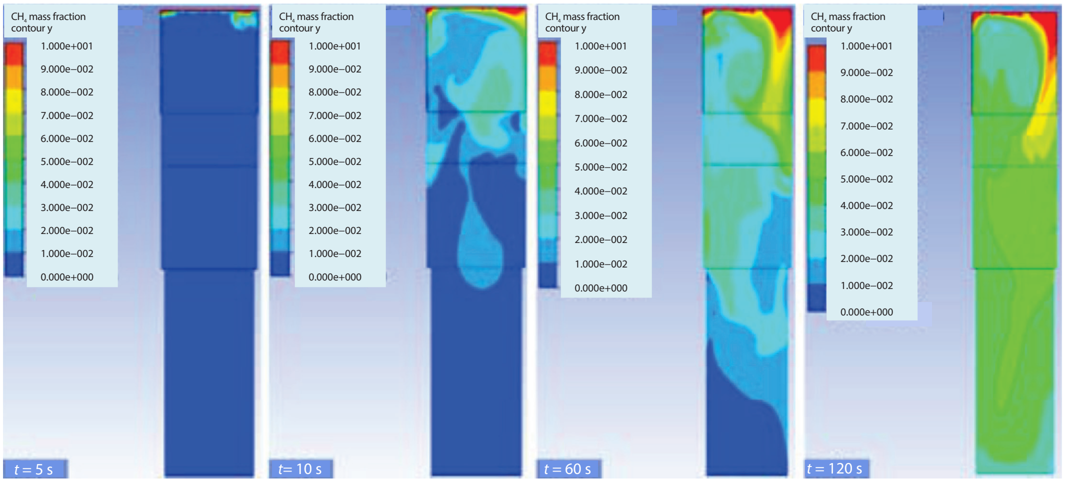

Figure 9. The CH_4 concentration distribution at flat profile

Gas tunnels currently under construction in China are all equipped with safety monitoring systems. The system mainly monitors the concentration of various gases in the tunnel by disposing corresponding gas sensors. For the convenience, most of these sensors are hanged on the tunnel jumbo or supply car. The arrangement of the sensors should be in accordance with the tunnel air-flow structure. However, for current constructions, the position and number of the sensors are mainly determined based on the importance of each sensor. For example, when gas sensors are deployed in the gas tunnel, a low-concentration CH_4 sensor is hanged on the left, right, and middle of the tunnel jumbo. The arrangement of CH_4 sensors should therefore, be in accordance with the spreading characteristics of CH_4.

Conclusions

In this study, the air-flow structure and CH_4 diffusion during the construction of gas tunnels were studied. A 3-D numerical model was established to investigate the air-flow and the hazardous gas in the tunnel during construction using the bench cut method. It appears that the construction of the bottom bench can significantly affect the air-flow structure of the tunnel in the re-circulation zone. However, calculation results displayed that the CH_4 does not accumulate inside the bottom bench. Although there is no need to worry about the accumulation of CH_4 in the bottom bench, the high concentration of CH_4 band is located on the side away from the duct. The main reason for the absence of gas accumulation in the bottom bench is that CH_4 density is lower than air density. Nevertheless, harmful gases which densities are higher than air density can be found. Gas such as NO_2 and dust, are very likely to accumulate in the bottom bench. Moreover, during the construction of the bottom bench, these elements will also be produced and will therefore, increase air pollution in the bottom bench. As the construction of the bottom bench is carried out throughout the whole tunnel construction process, the work environment in the bottom bench should also be given a great attention.

Nomenclature

c_s – volume concentration, [–]
D_s – diffusion coefficient, [m^2s^{-1}]
t – time, [s]

Greek symbol

ρ – mass density, [kgm^{-3}]

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