Research on Parameters Setting of Smoke Exhaust Outlet and Cross Passage on Side Wall of Underwater Tunnel

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Abstract. In recent years, the length and scale of underwater road tunnels have continued to increase. Ventilation and fire prevention have become one of the key control factors for the successful construction and safe operation of underwater road tunnels. As one of the smoke extraction schemes of highway tunnel, determining the layout of sidewall smoke outlet is very important. In this paper, for the purpose of people being able to evacuate safely in a tunnel fire accident, taking an underwater tunnel as an engineering example, the available safe evacuation time (ASET) and the required safe evacuation time (RSET) under different working conditions are compared and analyzed by simulating the fire smoke spread and personnel evacuation process in the tunnel, so as to provide quantitative basis for the arrangement scheme of sidewall smoke outlet.

1. Introduction

In recent years, more than 30 underwater highway tunnels have been built or under construction in China. In the future, China will also plan to build new underwater tunnels with a total length of more than 200 km. The construction scale and speed are among the highest in the world. Underwater tunnels have the advantages of not spending land, not interfering with shipping, not affecting the ecological environment, reducing the impact of the ground environment, and having a strong ability to withstand harsh weather conditions. Therefore, the construction of underwater tunnels has become a trend. However, because underwater tunnels are different from mountain tunnels in terms of geographic location, functional positioning, and environmental protection requirements, there is a lack of domestic standards for ventilation and fire protection of underwater tunnels [1-2]; In addition, there are few research and engineering cases on ventilation and fire prevention of underwater highway tunnels in China. Therefore, it is necessary to conduct in-depth and detailed research on the special technology of ventilation and fire protection of underwater super long highway tunnels. This paper takes a tunnel as an engineering example, with the goal of people and vehicles being able to evacuate safely during a fire, numerical simulations of the fire development process and the evacuation process are carried out, and the available safe evacuation time (ASET) and the required safe evacuation time (RSET) of people are analyzed and compared under different working conditions, so as to provide a quantitative basis for the layout setting of the smoke exhaust vent and the horizontal passage [4].
2. Engineering background

A tunnel has a total length of 10.87 kilometers and is a two-way six-lane. The cross-section adopts the form of a double-hole and one-pipe gallery. The single hole has a clear width of 17.45 meters and a clear height of 7.25 m. The middle pipe gallery has a width of 4.5 m and the upper part is a flue exhaust duct. The cross section of the tunnel is shown in Figure 1.

This tunnel is an ultra-long tunnel. The long-term forecast is that the traffic volume is large and the proportion of trucks is high, which has high requirements for tunnel operation ventilation, fire and escape rescue. Taking into account the problem of smoke removal in the event of a fire, the tunnel plans to use a sidewall smoke exhaust program, that is, a series of smoke outlets are set up on the sidewall of the tunnel to connect the smoke exhaust ducts on the upper part of the middle pipe gallery, and a certain amount of smoke outlets will be opened when a fire occurs to achieve the purpose of removing smoke, and the number of opening outlets, opening positions, opening areas, and cross-sectional wind speeds will affect the efficiency of the exhaust system. If the operation is careless, the exhaust system may fail. Therefore, it is necessary to carry out research on the layout of the side wall exhaust ports and the setting parameters of the transverse passage.

![Figure 1. Cross-sectional view of tunnel](image)

3. Fire simulation and analysis with the side wall smoke extraction scheme

3.1 Model building and working condition setting

When the calculation model is established, the size of the tunnel cross section is the actual size of the tunnel, the longitudinal length of the model is 500 m, the area of the fire source is 10 m×2.5 m, and the fire source is located at y=250 m in the longitudinal direction of the tunnel. The layout of the smoke exhaust port is designed separately according to different working conditions, as shown in Table 1.

| Test No. | Total volume Rate of Smoke Vents (m³/s) | Amount of Exhaust Vents Opened | Spacing of Exhaust Vents (m) | Velocity at Smoke Vents (m/s) | Longitudinal Air Velocity(m/s) |
|---------|--------------------------------------|-------------------------------|-------------------------------|------------------------------|-------------------------------|
| 1       | 210                                  | 4                             | 60                           | 8.75                         | 0                             |
| 2       | 6                                    | 6                             | 60                           | 5.83                         | 0                             |
| 3       | 6                                    | 6                             | 60                           | 5.83                         | 1                             |
| 4       | 6                                    | 6                             | 60                           | 5.83                         | 2                             |
| 5       | 4                                    | 8                             | 80                           | 8.75                         | 0                             |

3.2 Fire source parameter setting

The tunnel is a passenger urban road tunnel, mainly set for small passenger cars (the proportion of long-term microbus and midibus is as high as 94%). According to the relevant recommendations of the National Fire Protection Association (NFPA), the World Road Association Tunnel Committee (PIARC), and the investigation results of domestic tunnel fire accidents, considering the adverse working conditions, the design uses a fire heat release rate of 50 MW as the fortification standard [5-8],
the fire growth curve adopts the ultra-fast square growth model [9-10].

3.3 Simulation result analysis

3.3.1 Comparison of smoke diffusion range

The comparative analysis shows that the more the number of openings of the exhaust holes, the smaller the diffusion range of the smoke within a certain period, and the larger the arrangement spacing of the exhaust holes, the larger the diffusion range of the smoke within a certain period. The longitudinal wind speed has a significant influence on the diffusion of smoke. Under the influence of longitudinal wind speed, the spread of smoke is asymmetric, and it will spread more in the direction of the longitudinal wind, and the degree of influence will deepen as the wind speed increases.

3.3.2 Survival indicators at specific moments under various conditions

The indicators that affect human survival and evacuation, such as temperature, CO concentration, and plane visibility at a height of 1.8 m from the ground under five working conditions, are shown in the figure.
At a height of 1.8 m from the tunnel ground, the highest CO concentration never reached 1500 ppm, the temperature reached 60 °C at 431 s, and the visibility was lower than 10 m at 430 s, that is, the time to reach the hazard criterion during the fire condition 1 is 430 s. The results of other conditions are shown in the table below.

Table 2. Time when each test condition reaches the dangerous criterion (unit: s)

| Test No. | temperature≥60°C | CO concentration≥1500 ppm | visibility≤10 m | ASET(s) |
|----------|-------------------|----------------------------|----------------|---------|
| 1        | 430               | not exceeding              | 431            | 430     |
| 2        | 439               | not exceeding              | 439            | 439     |
| 3        | 408               | not exceeding              | 410            | 408     |
| 4        | 380               | not exceeding              | 380            | 380     |
| 5        | 436               | not exceeding              | 438            | 436     |

As can be seen from the tables above, in the range of working conditions 1 to 5, the number and spacing of the smoke exhaust openings have little effect on the available safe evacuation time. Longitudinal wind speed has a greater impact on the available safe evacuation. Therefore, when the number of openings of the exhaust holes and the distance between the exhaust holes remain unchanged, increasing the longitudinal wind speed will significantly reduce the available safe evacuation time.

4. Simulation of evacuation in the event of a fire in a tunnel

4.1 Evacuation scene and number setting

In the case of a tunnel fire, people in the fire tunnel are evacuated to the adjacent safety tunnel through the crosswalk. According to the actual parameters of the tunnel cross-section, a 500 m long tunnel was established to carry out the numerical simulation calculation of evacuation. A total of 4 evacuation exits were set up. The evacuation calculation model is shown in Figure 5, and the simulated conditions are shown in Table 4.

Figure 5. Schematic diagram of simulated evacuation tunnel

In this simulation, the number of people was estimated based on the worst case and serious traffic jams in the tunnel. The number of personnel is estimated according to the ratio of vehicle types. The
ratio of vehicle types, vehicle length and the number of personnel per vehicle are shown in Table 3. The distance between vehicles is 1.5 m. Therefore, it can be calculated that the number of people in the 500 m tunnel is 1146.

| Vehicle Type | buggy | Medium truck | large truck | container truck | car | bus |
|--------------|-------|--------------|-------------|-----------------|-----|-----|
| Proportion of vehicles | 4.40% | 12.30% | 8.30% | 5.80% | 62.60% | 6.60% |
| passenger capacity | 2 | 2 | 3 | 2 | 5 | 45 |
| Length of vehicle(m) | 6 | 8.5 | 12.5 | 20.5 | 5 | 11 |

4.2 Evacuation simulation conditions and results

We set up 5 working conditions with the layout spacing and width of the horizontal channel as variables, and the results are shown in Table 4.

| Test No. | Amounts of people to be evacuated | Spacing of cross-passage (m) | width of cross-passage (m) | RSET (s) |
|----------|----------------------------------|-------------------------------|---------------------------|---------|
| 1        | 1146                             | 60                           | 2                         | 230     |
| 2        | 1146                             | 80                           | 2                         | 243     |
| 3        | 1146                             | 100                          | 2                         | 257     |
| 4        | 1146                             | 125                          | 1.5                       | 315     |
| 5        | 1146                             | 125                          | 2                         | 284     |

The layout spacing and width of the horizontal aisles have varying degrees of impact on the evacuation time required for personnel. When the width of the cross aisles is the same, the distance between the cross aisles is increased, and the total evacuation time will also increase; when the cross aisles are kept constant and the width is slightly increased, the total evacuation time will be significantly reduced.

5. Conclusion

1. Under the circumstance of ensuring the same amount of smoke, small changes in the number and spacing of the smoke exhaust openings have little effect on the available safe evacuation time. Longitudinal wind speed has a great influence on the simulation results. The higher the wind speed, the less time available for evacuation. When a fire occurs, controlling measures should be emphasized.

2. The layout spacing and width of the pedestrian crossing have an impact on the required safe evacuation time (RSET). The time required for evacuation will increase with the increase of the layout of the pedestrian crossing, and decrease with the increase of the width of the pedestrian crossing. The arrangement of cross-walks with a spacing of 100 m and a width of 2 m is relatively advantageous for evacuation during a fire.

3. When the side wall exhaust method is adopted (exhaust amount of 210 m$^3$/s), the available safe evacuation time is between 380 s and 439 s. When the crosswalk is 100 m in spacing and 2.0 m in width, the time required for evacuation is 257 s, and the time available for personnel to escape under various working conditions is sufficient to meet the time requirements for evacuation.

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