



Study on the Influence of Gas Leakage Direction on Explosion Load in Utility Tunnel

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Abstract. Utility tunnel is an important link in the construction and operation of modern cities, and the entrance of gas pipelines into corridors has brought great challenges to the safety protection of utility tunnel. This paper focuses on the free diffusion gas clouds within model integrated utility tunnels as the test subjects, investigating the spatial distribution of gases and explosion loads under different gas leakage directions. The test results indicate that gas leakage in a utility tunnel will propagate from top to bottom, spreading from the near end to the far end, with the horizontal propagation velocity gradually decreasing from top to bottom. The upward leakage will form the most obvious vertical stratification phenomenon, and the downward and horizontal leakage will weaken in turn. Under the test conditions of this paper, there is a positive correlation between gas explosion load and propagation distance. And the peak gas explosion load is the highest under horizontal leakage conditions. Fire-resistant isolation under gas explosion load is the weak part of structural damage. The research findings provide a reliable basis for the design of utility tunnel disaster prevention and mitigation.

Keywords: Utility tunnel; Leakage direction; Concentration gradient; Gas explosion

1 Introduction

As a lifeline project of the city, utility tunnel has received many municipal pipe-lines. Among them, gas pipeline is widely concerned because of its flammable and explosive characteristics. The gas explosion accident is based on the premise that the gas pipeline is damaged and gas leaks. The research of many researchers shows that in the real scene, due to the difference between methane and atmospheric density, gas will be vertically stratified after leakage [1-2]. In order to study the law of gas explosion accidents under realistic conditions, many researchers have done a lot of research in gas-air mixture with concentration gradient [3-6]. By monitoring the methane concentration within a pipeline with a volume of 0.18 cubic meters, scholars have observed that, as the leakage persists, the impact of different ignition times on the propagation of the explosion flame

and the overpressure of the explosion becomes more pronounced. [7]. Moreover, some scholars have found that the vertical concentration gradient of gas will reduce the explosion load [8] and slow down the flame speed [9], and the horizontal concentration gradient enhances the instability of detonation [10]. As the root of explosion accident, the spatial distribution of gas after leakage will be affected by factors such as leakage direction, leakage speed and leakage aperture [11-12]. Therefore, the gas leakage condition will fundamentally affect the gas explosion load. However, in current research, the method of filling an adjacent closed space with a uniform premixed methane gas cloud is often used to generate a concentration gradient [13-14]. There are no examples of gas explosion tests that integrate the gas leakage process and consider gas leakage parameters. To address this deficiency, this paper first conducts gas leakage diffusion experiments to ascertain the distribution laws of the gas. Subsequently, by altering the leakage direction, different concentration gradients of methane gas clouds are generated. Finally, an explosion test was conducted to obtain the gas explosion load characteristics under different leakage directions. The test conditions are more realistic, with a view to revealing the development patterns of gas explosion accidents in the utility tunnel under realistic conditions.

2 Test Design

The internal clear height of the gas compartment is 1.2 m, with a clear width of 0.8 m, as illustrated in Figure 1. In order to simulate the sealing effect of fire-resistant isolation, both ends of the model structure are sealed with steel plates.

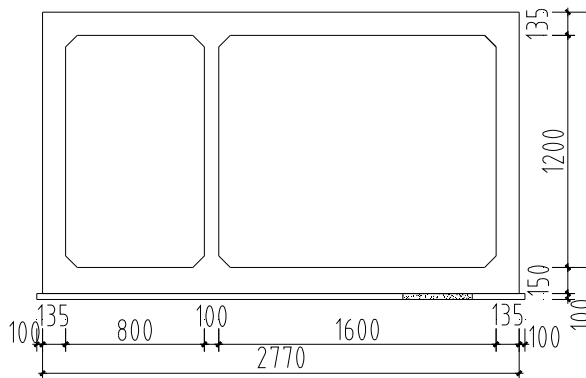


Fig. 1. Test model size

Methane accounts for more than 90% of natural gas, so bottles of methane gas were used instead of natural gas in the test. In gas leakage diffusion tests, methane sensors are used to measure the methane concentration at various measuring points within the structure. Methane sensors are arranged at a longitudinal spacing of 7.5m and a vertical spacing of 40cm to study the longitudinal and vertical propagation rules after gas leakage, as shown in Figure 2.

In this experiment, a pressure sensor with a range of 2MPa (allowing 130% over-range measurement) is used to measure the explosion overpressure in the model pipe gallery structure. The distance between sensors is 3m, the measuring points at both ends are 1.5m away from the mouth, and pressure sensors are also arranged at the steel plates at both ends. The arrangement of pressure sensors is illustrated in Figure 3.

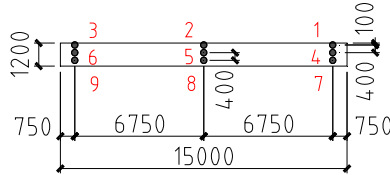


Fig. 2. Layout of methane sensor.

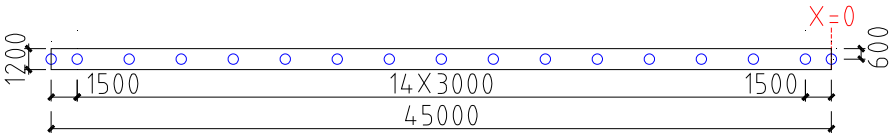


Fig. 3. Layout of pressure sensor.

In the gas explosion test, a remote high-energy igniter is used for ignition. During the test, the ignition rod is suspended at a certain height below the central top plate of the mixed gas cloud. The ignition energy of the ignition device is 20J.

3 Test Condition

In this experiment, methane was used as a substitute for natural gas, and explosion tests were conducted using a freely diffusing cloud of gas. The leakage hole was located near the partition wall at the center of the gas cloud, with a diameter of 4 centimeters. The leakage arrangement under different leakage directions is shown in Figure 4–6. During the test, the gas leakage velocity under each working condition is consistent, which is 6 m/s.



Fig. 4. Leak hole layout under upward leakage condition.



Fig. 5. Leak hole layout under horizontal leakage conditions.



Fig. 6. Leak hole layout under downward leakage conditions.

During the test, a 15m long closed space was sealed inside the structure with the longitudinal center of the structure ($x=22.5\text{m}$) as the symmetry axis, and the gas volume proportion in all tests was controlled to 9.5%. Since the methane sensor cannot withstand the high temperature and high pressure environment of a gas explosion, the gas leakage diffusion test and the explosion test must be conducted separately. Therefore, the leakage conditions in both tests must be identical. In order to minimize the influence of sealing section on gas explosion, concrete curing film with thickness of 0.05mm and 3M duct tape were used to seal the section. Before the formal test, the air pump was used to carry out the inflation test to ensure that there would be no gas leakage in the sealing section under the test conditions. The detailed experimental operating conditions are presented in Table 1.

Table 1. Test conditions.

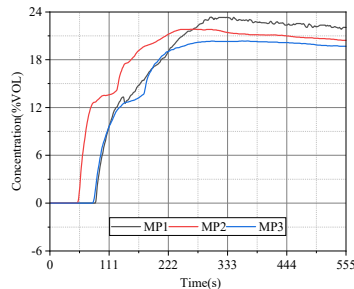
Conditions	Gas volume ratio (%)	Gas leakage direction	Ignition rod height (m)
L1	9.5	upward	/
L2	9.5	horizontal	/
L3	9.5	downward	/
E1	9.5	upward	/
E2	9.5	horizontal	0.6
E3	9.5	downward	0.6

4 Analysis of Test Results

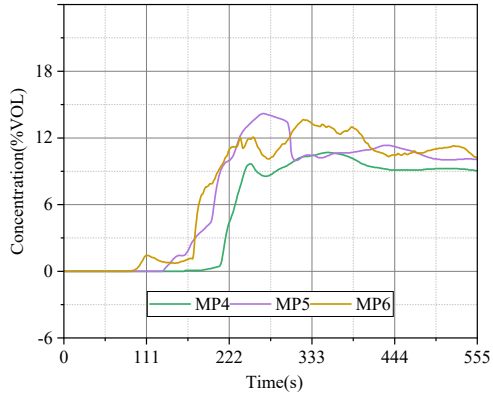
4.1 Gas Concentration Curves in the Structure Under Different Leakage Directions

Figure 7 to 9 are time-history curves of methane concentration under working conditions L1~L3. During the test, after reaching the preset leakage volume, the air inlet valve will be closed and let stand for a period of time. Under upward leakage conditions, there is a distinct vertical stratification phenomenon of gases within the structure. The methane concentration at 1.1m height is about 20~22%VOL, at 0.7m height is about 9~10% vol, and at 0.3m height is about 1% vol. In the downward leakage condition, the vertical stratification of gas is slightly weakened. The methane concentration at 1.1m height is about 11-13% vol, at 0.7m height is about 10-12% vol, and at 0.3m height is about 6-9% vol. Under horizontal leakage conditions, the vertical stratification of gases is least pronounced.. The methane concentration is about 11-13% vol at 1.1m height, 10-12% vol at 0.7m height and 8-9% vol at 0.3m height. This is because when the leakage speed is 6m/s, the horizontal leakage will make the gas jet reflect at the side wall of the structure, and the reflected jet will weaken the influence of buoyancy and make the gas distribution more uniform.

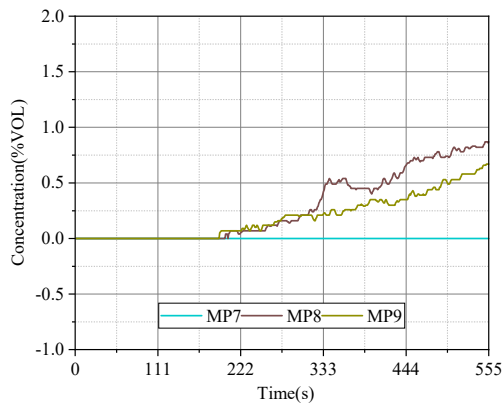
From the perspective of the diffusion process, the influence of buoyancy following gas leakage will initially propagate upwards to the upper part of the structure, and subsequently, driven by concentration gradients, spread downwards and from closer to farther distances. In the case of upward leakage, when all sensors on the roof detected methane, the sensors at the height of 0.7m and 0.3m near the leakage hole did not detect methane. However, this phenomenon is gradually blurred in the case of horizontal leakage and downward leakage. Under conditions of downward leakage, despite the simultaneous detection of methane by sensors at different heights near the leakage hole, the sensors on the upper plate, which are located farther away from the leakage hole, still detect methane first. Therefore, the horizontal diffusion rate of gas in the utility tunnel gradually decreases with height decreases. It can be seen from the above rules, at the beginning of gas leakage, the gas will be distributed in a trumpet shape along the longitudinal direction of the structure centered on the leakage location. As the volume of gas leakage increases, the gas will be distributed in an inverted trapezoidal shape along the longitudinal direction of the structure centered on the leakage location.



(a) At a height of 1.1m

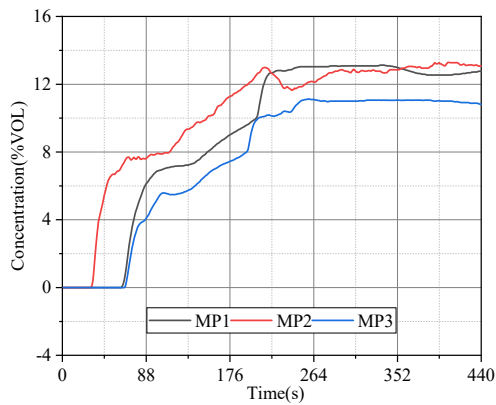


(b) At a height of 0.7m

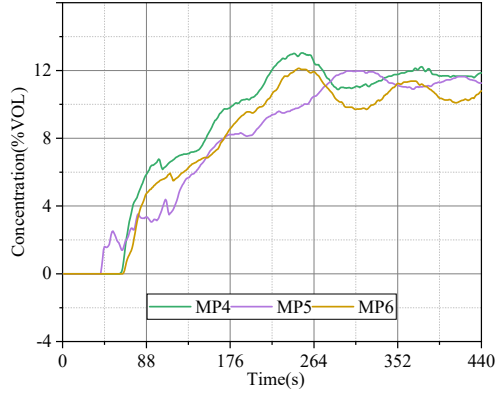


(c) At a height of 0.3m

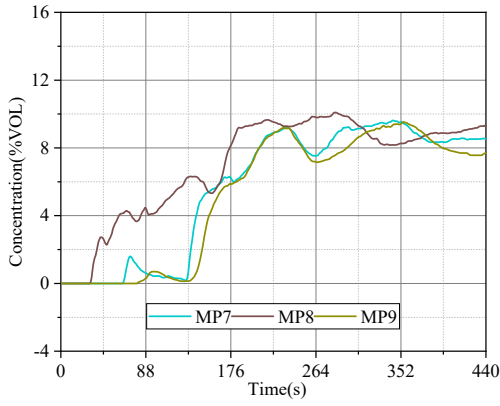
Fig. 7. Gas concentration curve in structure under upward leakage condition.



(a) At a height of 1.1m

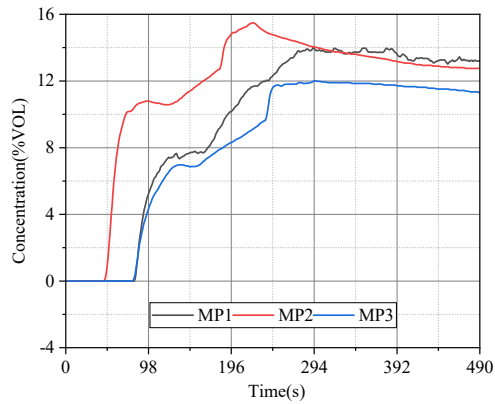


(b) At a height of 0.7m

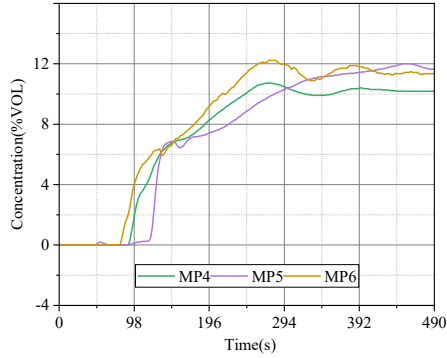


(c) At a height of 0.3m

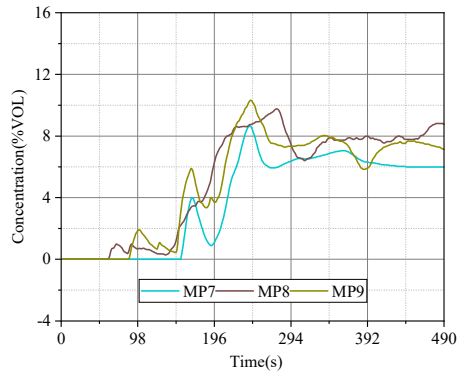
Fig. 8. Gas concentration curve in structure under horizontal leakage condition.



(a) At a height of 1.1m



(b) At a height of 0.7m



(c) At a height of 0.3m

Fig. 9. Gas concentration curve in structure under downward leakage condition.

4.2 Load Curve of Gas Explosion in Structure Under Different Leakage Directions.

Under the condition of upward leakage, due to the excessive gas concentration gradient, many attempts were made at different heights and different horizontal positions during the test, but the ignition was never successful. Figures 10 and 11 show the gas explosion load curves in the case of horizontal leakage and downward leakage respectively. In the test, the ignition position was located at the center of the structure and the mixed gas cloud. After ignition, the flame spread from the ignition position to both sides. Since the structural sections on both sides of the ignition position are exactly the same, and preliminary diffusion tests also show that the gas distribution on both sides of the ignition position is roughly the same, the flame and explosion load development processes on both sides of the ignition position are similar. Therefore, this article only analyzes the load time history curve of the measuring point on one side of the ignition position.

Under horizontal leakage conditions, the peak gas explosion loads at the ignition position (22.5m), 31.5m and the blocking position (45m) are 77.58kPa, 82.74kPa and

101.56kPa respectively. The minimum load appears at the ignition position and the maximum load appears at the blocking position. The peak load increases by about 31%. Under downward leakage conditions, the peak gas explosion loads at the ignition position (22.5m), 31.5m and the blocking position (45m) are 60.69kPa, 67.96kPa and 73.88kPa respectively. The minimum load appears at the ignition position and the maximum load appears at the blocking position. The peak load increases by about 22%. In the above two tests, the gas explosion load within the structure gradually increased as the propagation distance increased, and the maximum load appeared at the blocking positions at both ends of the structure. Therefore, when a gas explosion occurs in the utility tunnel, there is a positive correlation between the peak gas explosion load and the propagation distance in a certain area. The maximum value of the gas explosion load will appear at the fire-resistant isolation position. Since the fire-resistant isolation is generally a masonry structure, the fire-resistant isolation is the most vulnerable position to damage.

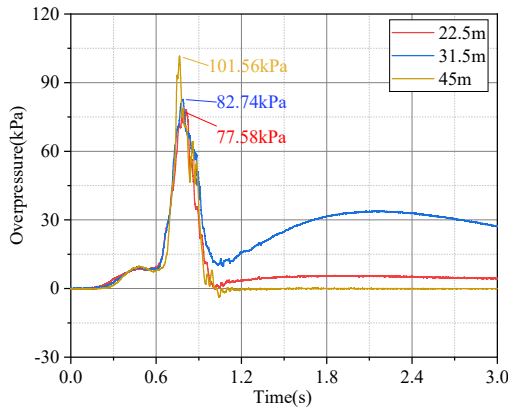


Fig. 10. Load curve of gas explosion in structure under horizontal leakage condition.

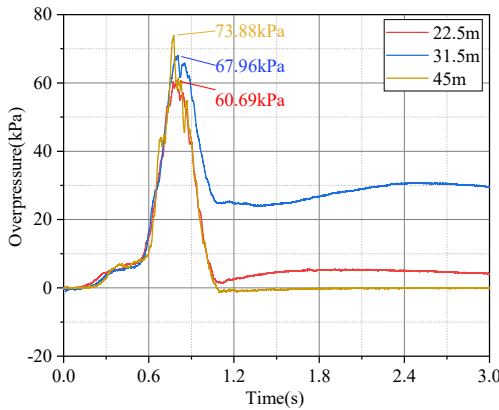


Fig. 11. Load curve of gas explosion in structure under downward leakage condition.

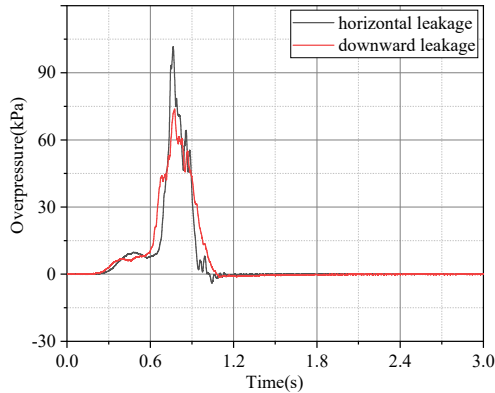


Fig. 12. Comparison of maximum load curves in horizontal leakage and downward leakage conditions.

As illustrated in Figure 12, the load curves with the highest peak values under both horizontal leakage and downward leakage conditions (with the load time history curve at the 45m measurement point selected) are compared. It can be seen that under horizontal leakage conditions, the maximum load peak of gas explosion is 106.99kPa, and the positive pressure duration is about 600ms. In the downward leakage condition, the maximum load peak of the gas explosion is 73.88kPa, and the positive pressure duration is about 750ms. The maximum load peak of the horizontal leakage condition is increased by about 45% compared with the downward leakage condition, and the positive pressure duration is shortened by about 20%. Under horizontal leakage conditions, both the initial load peak and the maximum load values are greater than those under downward leakage conditions, indicating that with more uniform gas distribution, the reaction during the gas explosion process is more intense.

5 Conclusions

This article conducted gas leakage diffusion experiments within a model utility tunnel, yielding insights into the diffusion and spatial distribution patterns of gas leakage. Furthermore, the study also investigated the influence of the leakage direction on the spatial distribution pattern of gas. On this basis, the whole process test of gas leakage and explosion was carried out to study the gas explosion load characteristics in different leakage directions. In order to provide guidance for the safety protection of utility tunnel. By analyzing the test results, it was found that:

(1) In utility tunnel, following the gas leak, the dispersion will propagate from top to bottom and from nearby to distant areas. As the altitude decreases, the horizontal propagation velocity of the gas will gradually diminish. Therefore, at the beginning of gas leakage, the gas will be distributed in a trumpet shape along the longitudinal direction of the structure centered on the leakage location. As the volume of gas leakage increases, the gas will be distributed in an inverted trapezoidal shape along the longitudinal direction of the structure centered on the leakage location.

(2) In utility tunnel, when gas leaks upward, there will be obvious vertical stratification, followed by downward leakage, and horizontal leakage stratification is the least obvious. The highest gas concentrations in the structure all appear in the roof position, which are about 22%VOL, 13%VOL and 13%VOL respectively. The vertical stratification of gas will significantly reduce the peak explosion load.

(3) When a gas explosion occurs within utility tunnel, there exists a positive correlation between the peak load of the gas explosion within a certain area and the distance of propagation. The maximum load of the gas explosion will be observed at the fire-resistant isolation location. The more uniform the gas distribution, the stronger the explosion reaction will be.

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