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Natural ventilation of urban shallowly-buried road tunnels with roof openings

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ABSTRACT

China has constructed a number of urban shallowly-buried road tunnels with roof openings, and their air quality has attracted favourable comments. However, no satisfactory theoretical model has been constructed for this type of tunnel and experimental data is lacking. Moreover, its design conflicts with existing building codes. It has been assumed that the pressure fluctuation produced by vehicle motion causes a respiratory phenomenon at the roof opening, with alternating inward and outward air exchange. However, some researchers have challenged this assumption. We conducted 12 groups of experiments using a 1/36-scale road-tunnel testing platform. We analysed three vehicle speeds and four roof-opening layouts. Supplemented by flow-field display technology, we tested the distribution of air velocities and the flow-field characteristics. Our major conclusions are as follows: (1) At a constant vehicle flow, the airflow at the roof opening was always from outside to inside, and no respiration phenomenon was observed. (2) The maximum inlet velocity was at openings near the tunnel entrance, and the velocity gradually decreased as the openings were placed deeper into the tunnel. The inlet velocity exhibited a concave curve along the tunnel length. (3) The number of roof openings had no significant impact on the inlet velocity, and it is inappropriate to treat the tunnel flow field as a conduit flow. (4) At a constant vehicle flow rate, roof openings provided a significant volume of ventilation, and the ventilation ability was different at different locations.

1. Introduction

As urban road traffic has continued to increase, urban road tunnels are being used to relieve the pressure of routine traffic. In contrast with standard tunnels, urban road tunnels are generally shallowly-buried tunnels, with depths of 1.0–5.0 m from the ground surface. These tunnels are normally mechanically ventilated using axial fans. Although this method assures air quality, it also creates high noise levels in the tunnel and consumes large amounts of power. A more effective approach to ensuring air quality is therefore required for such underground spaces (Chen et al., 2015; Chow et al., 2015; Ji et al., 2014; Kong, 2005).

Zhong et al. (2006) proposed the introduction of openings above these urban road tunnels to take the advantage of natural ventilation, requiring no mechanical ventilation or mechanical smoke extraction during fires. This approach gained favour with many urban construction departments in China.

The tunnels using this design include the Chengdu Hongxing Road Tunnel, which was opened in June 2005, with an underground length of 800 m, the Nanjing Tongjimen Road Tunnel, (April 2007; underground length of 890 m) and the Nanjing Xi'anmen Road Tunnel, (September 2007; underground length of 1410 m) (Fig. 1). In October 2008, the Nanjing Xinmofan Road Tunnel, with an underground length of 3000 m, was opened. The Nanjing Qinghuaihe Tunnel, currently under construction, also adopts this design.

The air quality in these tunnels has been widely praised and favourably contrasted with that in conventional road tunnels. However, there is no sufficient theoretical basis and experimental support to justify the design and construction of this type of tunnel. In addition, there is no systematic recognition on the ventilation mechanism on the roof openings. Further, the design of urban road tunnels conflicts with the Design Code of Ventilation and Lighting of Road Tunnels (JTJ026.1-99), which requires that one-way traffic tunnels utilize mechanical ventilation when the

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Fig. 1. Nanjing Xi'anmen Tunnel with roof opening.

product of the tunnel length and vehicle flow is greater than 2000 (cars × km/h). Modic (1998, 2003a, 2003b) has pointed out that when the volume of traffic is less than 750 cars per hour and the vehicle speed is greater than 30 km/h, this gives an allowable tunnel length of up to 3000 m. However, the requirement is only for tunnels without roof openings, as the existing code regards roof openings as detrimental to tunnel ventilation.

In 2010, based on a number of research studies (Bogdan et al., 2008; Ingason and Wickström, 2006; Palazzi et al., 2005; Tong et al., 2009; Wong et al., 2006; Zhong et al., 2006; Zhong and Zeng, 2006), Jiangsu Province issued and implemented the Design and Acceptance Code for Urban Tunnel Shaft Type Natural Ventilation (DGJ32/TJ102-2010). This code requires that the interval between roof openings be less than 240 m and, for tunnels between 500 m and 1500 m in length, the opening rate (effective opening area/tunnel horizontal projection area) be greater than 3.25%. However, due to the lack of mature theory and the scarcity of supporting data, local administration construction departments and fire-fighting agencies expressed concerns about this type of tunnel design. In response, further studies were conducted (Barbato et al., 2014; Blocken, 2014; Bubbico et al., 2014; Fan et al., 2014; Jin et al., 2015; Levoni et al., 2015; Li et al., 2015; Musto and Rotondo, 2015; Wang et al., 2015). Most of these were theoretical studies of the flow field of this type of road tunnel, using conduit flow theory. The traffic through the road tunnel was assumed to be constant and continuous, and the flow field in the tunnel was assumed to be a one-dimensional conduit flow. It was also assumed that in a one-way road tunnel with multiple openings at the top or in the side walls, the air movement due to vehicle motion would create pressure fluctuations at the openings. The resulting pressure difference would then produce respiratory phenomena at the openings and lead to repeated air exchanges between the interior and exterior. These studies greatly improved our understanding of the process of natural ventilation in this type of road tunnel. However, some questions remain unanswered. First, the above theory is based on the conduit assumption of the tunnel flow field, but this assumption remains controversial. Moreover, most of these research outcomes have not been validated experimentally or largely deviate from experimental data. These deviations have been attributed to flow-field pulsation produced by vehicle motion or to testing uncertainty, but it is possible that they were simply due to errors in the theoretical models. This is plausible because some investigators, including the authors of this study, have not experimentally observed this respiratory phenomenon at roof openings and the flow-field characteristics that have been observed are significantly different from conduit flow.

In this study, therefore, we established a 1/36-scale model of a road tunnel, as a natural ventilation experimental platform. Flow-field display technology was used to measure the direction of airflow at the roof opening. We then measured the air velocity distribution at the openings and analysed the hourly characteristics and ventilation efficiency of the airflow.

2. Model experimental platform for natural ventilation of a road tunnel

2.1. Similarity theory for model experiment

The airflow in road tunnels is created by vehicles moving through a restricted space (Jin et al., 2015). The airflow velocity must be less than the speed of sound, and the corresponding Mach number must be significantly less than 1. The compressibility of the air could therefore be neglected in our experiments, and the tunnel air was treated as an ideal gas. In addition, as the study focused on the tunnel flow-field characteristics, only flow similarity was considered. The primary objective was to achieve comparable Reynolds (Re) values. As the geometric scale of the model was 1/36, an airflow with a speed 36 times that in the actual tunnel had to be generated. However, this not only precluded the achievement of similarity, but was unachievable. Fortunately, the self-modelling phenomenon allowed the experimental realization of partial similarity of the flow field. Additionally, the movement of vehicles subjects a tunnel airflow to disturbances much larger than those due to wall roughness. A tunnel flow field more readily enters a turbulent state than conduit flow in an identical cross-section. Experimental investigations (Aydin and Leutheusser, 1991; Zhu et al., 2008) have suggested that, when $Re > 7000$, the tunnel flow field enters a turbulent state. The characteristic length of the experimental model is the equivalent diameter of the model tunnel, i.e. $l = 0.17$ m. For the tunnel flow field to enter the turbulent state, the average air speed in the tunnel should be greater than 0.63 m/s. Jin et al. (2015) showed that under even and continuous vehicle flow, the average air velocity u and vehicle speed in a road tunnel v_0 are in the relationship $u = 0.5255v_0 - 0.01742$. Therefore, for the flow field to enter the turbulent state, the model vehicle speed should be greater than 1.24 m/s. We therefore used model vehicle speeds of 1.5, 2.0 and 2.5 m/s.

2.2. Experimental platform and testing plan

We used a two-lane mechanical testing platform. The model tunnel had a cross-section of 220 mm × 140 mm, an overall length of 8 m and a geometric scale of 1/36 (Figs. 2 and 4). The two sides of the model tunnel were enclosed in glass to allow observation, and movable glass plates were installed at the top. A conveyer belt was used to drive the model vehicles. The road of the model was