Train-induced unsteady airflow (TIUA) characteristics of track area in subway station with platform screen doors (PSDs)

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Abstract. Train-induced unsteady airflow (TIUA) has a great effect on the ventilation and thermal environment of a subway line. Track area, connecting tunnel with station, is the source of the TIUA acting on subway station. Exploring the TIUA characteristics of track area contributes to utilizing the TIUA for improving the tunnel and station environment. In this study, a 1D numerical model according to an actual subway line was established by IDA Tunnel software, to analyse the TIUA rates through the inbound and outbound ends of track area in the PSDs subway station. Four key factors, namely, train arrival time interval between both tunnels, train interval, operation modes of piston vent shafts and bypass ducts, were analysed. The results demonstrate that the TIUA rates of track area in PSDs subway station (bypass ducts closed) are mainly affected by the train driving in this tunnel. The TIUA rates of track area decreases about 36%–41%, as the train interval increases from 180 s to 540 s. By adjusting the operation modes of piston vent shafts, the change of TIUA rates of track area can reach up to about 13%–27%. By opening bypass ducts, the TIUA rates of track area decreases by 42%–50%.

1 Introduction

By the end of 2020, 178 cities in 57 countries and regions around the world had built subway lines, with a total mileage of 17585 km[1]. And 38 cities on Chinese mainland had operating subway lines, with a total mileage of 6281 km, accounting about for 40% of the total mileage of the world's subway[2]. However, as a long and narrow underground building space with strong tightness, its ventilation, thermal environment and air quality have attracted extensively concern. The above problems are closely related to train-induced unsteady airflow (TIUA), which is produced by the trains running in the tunnel[3]. Track area, the tunnel section around the subway station, is the key part connecting the tunnel and the station. Finding out the TIUA characteristics of track area conduces to estimate the TIUA rates flowing into the tunnel and station, and further improves the tunnel and station environment. Thus, research on TIUA characteristics of track area is significant.

At present, many researchers had investigated TIUA using theoretical analysis, field tests, and numerical simulation. First, for the single-track tunnel with a train running at a constant speed, the calculation formula of air velocity in the tunnel was proposed by X. Jin and W. Chen [4]. Then, for the train running at a variable speed in a single-track tunnel, a series of calculation formulas were put forward by X. Shen [5]. However, an actual subway line is composed of long tunnels, dozens of stations, and multiple trains, so complex transient airflow is generated. Therefore, it is difficult to apply the analytical formula of a single-track tunnel to the whole subway line condition. Further, S. Wang et al., and J. Qi et al., conducted the field test to monitor the air velocity in the subway tunnel[6, 7]. However, due to the limitation of field test situations, it is difficult to systematically analyse the TIUA characteristics and its influencing factors. With the progress of computer technology, CFD simulation has been increasingly adopted to analyse the TIUA characteristics. M.L. Gonzalez et al., established a 3D numerical model including two adjacent stations by using FLUENT software, to analyse the influence of TIUA on the longitudinal ventilation system of subway tunnels[8]. A. Khayrullah et al., analysed the effect of TIUA on the underground passenger platform employing FLUENT software [9]. However, due to the limitation of computer performance and calculation time, CFD simulation is generally difficult to accomplish the long subway lines and multiple trains driving. Thus, 1D simulation software was recommended to study the TIUA characteristics in a long subway line.

The current research aims to clarify the TIUA characteristics of track area. Based on an actual subway line, a 1D numerical model was established using IDA Tunnel software, to analyse the TIUA characteristics of track area and its influencing factors, including the train arrival time interval between both tunnels, train interval, operation modes of the piston vent shafts and the bypass...
ducts. This study provides significant guidance for controlling and utilizing TIUA and optimizing the operation mode of the environmental control system.

2 Numerical method

2.1 Description of IDA Tunnel

IDA Tunnel software, which is a 1D dynamic simulation software developed by EQUA, Sweden, can carry out the ventilation and fire simulation of road and rail tunnels. Based on an actual subway project, a numerical model including five subway stations and six tunnels. Based on the governing equations of IDA Tunnel software for airflow and heat transfer are as follows[3].

Continuity equation:

\[
\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(u^2) = 0
\]

Momentum equation:

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} \right) = \rho f \frac{\partial^2 u}{\partial x^2} + \rho g
\]

Energy equation:

\[
\rho \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} \right) = \rho \frac{\partial}{\partial x} \left( \frac{2(\partial u)}{\partial x} + S \right)
\]

Where, \( u \), velocity vector, m/s; \( \rho \), static pressure, Pa; \( V \), kinematic viscosity, m²/s; \( S \), source terms, W/m³; \( \mu \), air viscosity, kg/(m·s); \( K \), thermal conductivity, W/(m·°C); \( f \), body force, m/s²; \( T \), temperature, °C.

2.2 Physical model

Based on an actual subway project, a simplified 1D numerical model including five subway stations and six tunnel sections was established by IDA Tunnel software, as shown in Fig 1. Five subway stations have the same structural dimensions, as shown in Table 1. And the air leakage gap area and sliding doors area on one side of the platform are 1.2 m² and 54 m², respectively.

Fig. 1. Schematics of subway station C in 1D model.

Table 1. Parameters of the subway station

<table>
<thead>
<tr>
<th>Name</th>
<th>Size (L × W × H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall</td>
<td>98 m²×20 m ×5 m</td>
</tr>
<tr>
<td>Platform</td>
<td>136 m²×12 m ×4.5 m</td>
</tr>
<tr>
<td>Entrances</td>
<td>60 m²×6 m ×3 m</td>
</tr>
<tr>
<td>Piston vent shafts</td>
<td>100 m × 5 m × 4 m</td>
</tr>
<tr>
<td>Bypass ducts</td>
<td>12 m×6 m ×5 m</td>
</tr>
</tbody>
</table>

2.3 Parameter Settings

In this study, the “train interval (T)” refers to the time spacing between two trains arriving at the station successively in the same tunnel[10]. The “train arrival time interval between both tunnels (Δt)” represents the time spacing between the arrival two successive trains running in opposite directions from both side tunnels of the platform [10]. They are listed in Table 2. The train dwell time is set to 30 s. The maximum speed of the train is 16.7 m/s. The operation conditions of the piston vent shafts and bypass ducts are listed in Table 3 and Table 4, respectively. The positions of the dampers 1~6 are shown in Fig.1. To reduce the interference of thermal pressure ventilation, no heat source is set in this model[11]. In addition, the numerical method had been verified in the previous studies[12, 13].

Table 2. Train intervals (T) and train arrival time intervals between both tunnels (Δt)

<table>
<thead>
<tr>
<th>Train arrival time interval (Δt)</th>
<th>Train intervals (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 s</td>
<td>0</td>
</tr>
<tr>
<td>300 s</td>
<td>0</td>
</tr>
<tr>
<td>360 s</td>
<td>0</td>
</tr>
<tr>
<td>420 s</td>
<td>0</td>
</tr>
<tr>
<td>540 s</td>
<td>0</td>
</tr>
<tr>
<td>1/12T</td>
<td>15</td>
</tr>
<tr>
<td>2/12T</td>
<td>30</td>
</tr>
<tr>
<td>3/12T</td>
<td>45</td>
</tr>
<tr>
<td>4/12T</td>
<td>60</td>
</tr>
<tr>
<td>5/12T</td>
<td>75</td>
</tr>
<tr>
<td>6/12T</td>
<td>90</td>
</tr>
</tbody>
</table>

Note: the train only driving in one side of tunnel is used as a comparative condition.

Table 3. Operation conditions of piston vent shafts

<table>
<thead>
<tr>
<th>Mode</th>
<th>Open</th>
<th>Close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed system</td>
<td>/</td>
<td>Damper 1~4</td>
</tr>
<tr>
<td>Opening piston vent shafts at the inbound end of station</td>
<td>Damper 1, 3</td>
<td>Damper 2, 4</td>
</tr>
<tr>
<td>Opening piston vent shafts at the outbound end of station</td>
<td>Damper 2, 4</td>
<td>Damper 1, 3</td>
</tr>
<tr>
<td>Double piston vent shafts</td>
<td>Damper 1~4</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 4. Operation conditions of bypass ducts

<table>
<thead>
<tr>
<th>Mode</th>
<th>Open</th>
<th>Close</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closing bypass ducts</td>
<td>/</td>
<td>Damper 5,6</td>
</tr>
<tr>
<td>Opening bypass ducts</td>
<td>Damper 5,6</td>
<td>/</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Influence of train arrival time interval between both tunnels

In the PSDs subway station, the typical operation mode of “opening piston vent shafts at the outlet end of station” and “closing bypass ducts” was selected to analyse the TIUA rates in the track area. The train interval was 180 s. Figs. 2 (a)−(d) show the periodic variation of TIUA rates at inbound and outbound ends of track area affected by different train arrival time intervals between both tunnels (Δt). As shown in Figs. 2 (a) and (b), the TIUA rates at the inbound end of track area increase first and then decrease during the train arriving; but it keeps dropping as the train leaves. As displayed in Figs. 2 (c) and (d), the TIUA rates at the outbound end of track area increase first and then decrease during the train arriving and departing. The reason is the inbound end of the track area is far away from the departing train, and the
opening of the piston vent shaft at the outbound end of the station greatly weakens the sucked effect of the departing train on the track area. Thus, the TIUA rates at the inbound end of the track area keep dropping as the train leaves. In addition, the periodic variations of TIUA rates through track area are consistent under different train arrival time intervals between both tunnels \( (\Delta t) \), as shown in Figs. 2 (a)–(d). It indicated that the TIUA rates through the track area are mainly affected by the train driving in this side tunnel.

Further, based on the data in Figs. 2, the average TIUA rates over one train interval \( (T) \) cycle was calculated. As shown in Figs. 3 (a) and (b), it illustrates that the change of the average TIUA rates at the inbound and outbound ends of track area with train arrival time interval between both tunnels \( (\Delta t) \) is lower than 1.48% and 2.48%, respectively; which further confirms that the TIUA rates of track areas at the PSDs subway station are mainly caused by the train driving in this side tunnel.

### 3.2 Influence of train interval

To study the influence of train interval \( (T) \) on the TIUA rates of track area, the average TIUA rates of different train arrival time intervals between both tunnels \( (\Delta t) \) were calculated. As shown in Fig. 4, as the train interval \( (T) \) increases from 180 s to 540 s, the TIUA rates at the inbound and outbound ends of track area decrease about 41% and 36%, respectively. By comparison, it is found that there is a lower decrease rate of TIUA rates at the outbound end of track area. The reason is that the effect of train driving on the airflow at the outbound end of track area was weakened by opening piston vent shaft at the outbound end of station.

### 3.3 Influence of operation modes of piston vent shafts

In the PSDs subway station, the influence of four operation modes of piston vent shafts on TIUA rates of track area was analysed, based on the bypass ducts closed conditions. As shown in Figs. 5 (a) and (b), under different operation modes of piston vent shaft, the average TIUA rates of track area from large to small is in the following order: closed system > single-piston vent shaft (piston vent shafts at the inbound/outbound end of station)> double piston vent shafts. A detailed analysis of a single piston vent shaft is as follows.

For average TIUA rates at the inbound end of track area, as shown in Fig. 5 (a), the opening piston vent shaft at the outbound end of the station is higher than that at the inbound end. The reason is that the TIUA effect at the inbound end of the track area is more significant during the train arriving, but opening the piston vent shaft at the inbound end of the station will divert the TIUA in advance, so the TIUA rates at the inbound end of track area will greatly attenuate.

For average TIUA rates at the outbound end of track area, as shown in Fig. 5 (b), opening piston vent shaft at the inbound end of the station is greater than that at the outbound end when the train interval is 180 s. However, when the driving train interval is 360 s and 540 s, the opposite is true. The reason is that when the train interval is small enough, the piston vent shafts closer to the train have a more significant effect on the TIUA of track area. That is, for the piston vent shaft at the outbound end, the "suction effect" is more significant during the train departing. But the TIUA effect of the departing train is intercepted in advance by piston vent shafts, which greatly weakens the TIUA effect on the outbound end of track area. However, as the train
interval increases, the role of piston vent shafts further away from the train is gradually reflected. Namely, opening piston vent shaft at the outbound end contributes to increasing the TIUA rate of track area during the train arriving, as shown in Fig. (6).

Above all, in the PSDs subway station and bypass ducts closed mode, opening the piston vent shaft will reduce the TIUA rates of track area. Moreover, when the train interval is 180 s~540 s, the change of TIUA rates of track area by adjusting the operation modes of the piston vent shafts can be as high as about 13%~27%.

Fig. 5. Influence of different operation modes of piston vent shafts on the train-induced unsteady airflow (TIUA) rates of track area: (a) at the inbound end of track area, (b) at the outbound end of track area.

4 Conclusions

In the PSDs subway station, the TIUA characteristics of track area and four key factors were analysed, including train arrival time interval between both tunnels(Δt), train interval (T), operation modes of the piston vent shafts and the bypass ducts. When the train interval was 180 s~540 s, the following findings can be summarized.

(1) The TIUA rates of track area with the bypass ducts closed are mainly affected by the train driving in this side tunnel.

(2) The TIUA rates of track area decreases about 36%~41%, as the train interval increases from 180 s to 540 s.

(3) Opening the piston vent shafts will reduce the TIUA rates of track area. By adjusting the operation modes of the piston vent shafts, the change of TIUA rates of track area can be as high as about 13%~27%.

(4) The TIUA rates of track area decreases by 42%~50%, due to open bypass ducts.

References

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5. X. Shen. Study on piston wind characteristics of underground railway. TONGJI UNIV. (2004)