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Influence of tunnel aerodynamic effects by slope of equal-transect ring oblique tunnel portal

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ABSTRACT

This study uses a three-dimensional, compressible, turbulence model to investigate the alleviation effect on tunnel aerodynamics of equal-transect ring oblique tunnel portals with different slope values. The turbulent flow around the train body is computed using the RNG κ-ε turbulence model, and a sliding mesh method is utilized to treat the relative motion of train and tunnel. The numerical results are verified through the results of moving model experiments. The mitigation effects of ring oblique tunnel portal on the initial compression wave are analyzed. The relationship of micro-pressure wave and slope values is proposed, by which the micro-pressure wave induced by high-speed train entering tunnel with equal-transect ring oblique tunnel portal can be estimated rapidly. The accuracy of the proposed relationship is validated by previous studies and moving model experimental data. The estimation results using the proposed formula are in good agreement with data from references and moving model experimental tests. Results also show that the maximum pressure gradient and micro-pressure wave can be reduced by about 10.8% when slope value is 1:1.75 relative to slope value of 1:0.5.

1. Introduction

Strong pressure changes and a micro-pressure wave are generated when a train enters a tunnel at high-speed, which impacts on the comfort of passengers and the environment around the tunnel (Murray and Howe, 2010; Wang et al., 2015). Mitigation of these transient pressures and micro-pressure wave effects remains an ongoing technical challenge in the design of high-speed railway tunnels. There are numerous tunnels along high-speed railways in China, and most high-speed railway lines were designed to support train speeds of 350 km/h. At present, the normal operation speed of high-speed railway is faster than 300 km/h for many railway lines, and the aerodynamic effects in tunnels have become more serious. To ensure a high-speed train's safe passage through a tunnel without a speed reduction, tunnels with large cross sections (most often 100 m^2) were widely implemented in China (Peng et al., 2013). Tunnel portals are required under either of the following two conditions: (1) when no buildings exist within 50 m of the tunnel's exit, and the amplitude of the micro-pressure wave is greater than 50 Pa at the distance of 20 m from the tunnel exit; and (2) when buildings exist within 50 m of the tunnel's exit, and the amplitude of the micro-pressure wave is greater than 20 Pa at the building locations (Geng et al., 2006; Zhao et al., 2004). Thus, tunnel portals combined with other methods are often used for the mitigation of the transient pressure and micro-pressure wave. Oblique tunnel portals with the same cross-sectional area as the tunnel have been favored, which have lower space and cost requirements than enlarged tunnel portals (Liu et al., 2010).

Hara (1965) established the characteristic line solution method for tunnel pressure waves based on the one-dimensional flow hypothesis, and then Yamamoto (1969) used one-dimensional unsteady flow theory to revise the findings by Hara (1965) and proposed a method to calculate the friction coefficient using the initial compression wave. Subsequently, Woods and Pope (1976) used this one-dimensional method to simulate the initial compression wave induced by the train's entry into the tunnel, and gave the change laws of the initial compression wave. Based on these studies, one-dimensional flow theory was used to investigate the effects of conical tunnel portals on the initial compression wave pressure gradient and micro-pressure wave (Fox and Vardy, 1973; Vardy and Dayman, 1979). Numerical simulation that was carried out firstly by Réty and Grégoire (2002) to investigate the effects of the tunnel entrance's hood shape and perforations on the compression wave pressure gradient. Similarly, Howe (1999) studied the influence of tunnel portal flaring on the initial thickness of the compression wave and found that the shape of

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the flared portal is optimal when the pressure gradient across the front is constant and an overall minimum, so that the pressure in the wavefront increases linearly. Then Howe et al. (2003) considered the effects of an unvented tunnel entrance hood and found that the compression wave was generated by two successive interactions: (1) the train nose interacting with the hood portal and (2) the train nose interacting with the hood-tunnel junction. Howe et al. (2006, 2008) subsequently developed and validated a numerical procedure for rapidly predicting the compression wave generated by a high-speed train entering a tunnel. Numerical predictions were compared with experimental results to extend the numerical method's range of applicability. Xiang and Xue (2010) compared nine perforated tunnel entrances (with no section discontinuities between the hood and tunnel) and found that the proposed optimal hood reduced the temporal pressure gradient by approximately 43%. Uystepruyst et al. (2013) carried out an optimization of tunnel hood using numerical simulation methods. Conclusions in this study indicated that a constant section hood is the most efficient shape when compared to varying (elliptic or conical) section hoods. In addition, the temporal gradient of the pressure wave can be reduced by half through the optimization of the ratio between the hood and tunnel sections, and pressure gradient can be reduced significantly when the hood's length is in the range of 2–8 times the length of the train nose. Winslow et al. (2005) carried out theoretical investigation on initial compression wave characteristics produced by train entering a tunnel with a scarfed tunnel portal. It is concluded that decreases in gradient of initial compression wave are possible (up to about 15%) for scarf walls extending a distance beyond the tunnel entrance of the order of the tunnel height, but little or no additional improvement is achieved with longer walls. Liu et al. (2010) studied the influence of tunnel portal parameters on pressure change and micro-pressure wave using three-dimensional numerical simulations with purpose of optimizing the parameters of the designed tunnel portals and found that the micro-pressure wave decreased with the decrease of the slope value. In addition, moving model experiment was also performed to validate the accuracy of numerical methods. Liu et al. (2016) next considered the effects of two different tunnel portals on micro-pressure waves induced by a high-speed train entering a tunnel, but the focal point of this work was the effect of increased thickness linings on micro-pressure waves. Heine and Ehrenfried (2014) investigated the effects of enlarged tunnel portals on the pressure gradient and proposed an optimized portal that reduced the pressure gradient by 44%. Without regard to the specific moving model facility or device used, a number of studies have characterized the pressure waves generated by high-speed trains in tunnels (Doi et al., 2010; Endo et al., 2014; Ozawa and Maeda, 1988; Sasoh et al., 1998; Takayama et al., 1995). The methods and results obtained in these prior studies are of great value. However, the continued increase in train speeds and implementation of different types of tunnel portals along high-speed railway lines motivates further study and experimental simulation.

Oblique tunnel portals are widely used on high-speed railway tunnels around the world. Parameter optimization of the oblique tunnel portal is of great importance for the alleviation of pressure gradient and the micro-pressure wave induced by the entry of train. This issue has resulted in significant attention from experts and scholars, with a number of phenomena and research results having been found. However, there are still certain aspects that need to be studied further, for example, the relationship between the micro-pressure wave and the slope values of oblique tunnel portal. This numerical study is part of an effort toward the design of oblique tunnel portal with the same cross section area of tunnel. The main purpose of this paper is to study the influence on pressure gradient and micro-pressure wave by slope values, in order to give the explanation of the mitigation mechanism on the initial compression wave and summarize the relationship between micro-pressure wave and the slope values of equal-transect ring oblique tunnel portal. The train speed in this study was 350 km/h. The slope values of equal-transect ring oblique tunnel portals were 1:0.5, 1:0.75, 1:1.0, 1:1.25, 1:1.5 and 1:1.75, separately. The transient pressure and micro-pressure wave were obtained. Finally, the mitigation physical mechanism of initial compression wave by ring oblique tunnel portal was analyzed, and the relationship of micro-pressure wave and slope values is proposed, by which the micro-pressure wave can be estimated rapidly when slope value of equal-transect ring oblique tunnel portal is given.

2. Numerical model

2.1. Methodology

The airflow induced by a high-speed train entering a tunnel is confined by the limited space in tunnel, so the influence of compression should be taken into account even if the Mach number is less than 0.3. The speed of the train was 350 km/h in this study, and the height of the train (H), treated as the characteristic length, is 4.14 m. Thus, the Reynolds number of the flow field around the train calculated by formula (1) is 2.71×10^7. According to the study by Niu et al. (2017), when Reynolds number is larger than 3.3×10^6, the flow around the train is in a turbulent state.

$$Re = \frac{\rho VH}{\mu} \tag{1}$$

where the air density ρ is 1.225 kg/m^3, V is the train speed, and the air viscosity coefficient μ is 1.82×10^{-5} Pa s.

Simulation method based on Reynolds-averaged Navier–Stokes (RANS) equations has been widely used in the research of the aerodynamic performances induced by train passing through a tunnel (Baron et al., 2001; Mok and Yoo, 2001; Ogawa and Fujii, 1997; Xue et al., 2014; Yao et al., 2014). The aerodynamic performances were simulated by a three-dimensional, compressible, RNG κ-ε turbulence model in this study. The RNG κ-ε model was developed by Yakhot and Orszag (1986) using the Renormalization Group (RNG) method. It is similar to the standard κ-ε model but includes an additional term in the dissipation rate ε equation for interaction between the mean shear and turbulence dissipation. It also improved the predictions of heat and mass transfers near the wall (Chu et al., 2014), and in this study, the RNG κ-ε turbulence model and a sliding mesh method was utilized to simulate the aerodynamic waves generated by the trains passing through each other in a tunnel. Liu et al. (2017) used the RNG κ-ε turbulence model simulated the alternating pressure induced by a train running through a tunnel, and analyzed the influence of pressure loads on the dynamic responses of train. The RNG κ-ε turbulence model was also utilized by Niu et al. (2017) to simulate the aerodynamic performance of a metro train running between two adjacent platforms in a tunnel. In this work, the effects of acceleration and speed of the metro train, and of platform spacing, on the alternating pressure on the train and in the tunnel are studied. Huang et al. (2010, 2012), Rabani and Faghih (2015) used the RNG κ-ε turbulence model to simulate the pressure waves caused by trains running through a tunnel. The RNG κ-ε turbulence model is widely used in simulating the pressure wave in tunnels. In this study, RANS equations and the RNG κ-ε double equation turbulence model were used, and the governing equations are the continuity equation and the RANS equations, as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{2}$$

$$\rho\left(\frac{\partial \overline{u}}{\partial t} + u_k \frac{\partial u_i}{\partial x_k}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(-\rho \overline{u_i' u_j'}\right) \tag{3}$$

where u and p are the averaged velocity and pressure, respectively, ρ is the air density; μ is the air dynamic (molecular) viscosity. The subscripts $i, j = 1, 2, 3$ represent the x, y, z directions, respectively. The term $-\rho\overline{u_i' u_j'}$ is the time-averaged Reynolds stresses, representing the turbulent