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Influence of the geometry of equal-transect oblique tunnel portal on compression wave and micro-pressure wave generated by high-speed trains entering tunnels

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A R T I C L E I N F O

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A B S T R A C T

Pressure gradient and micro-pressure wave induced by a high-speed train entering a tunnel were investigated for the parametric design of equal-transect oblique tunnel portal. A moving model experimental test was conducted to verify the computational method and mesh. The influence of three main factors (portal shape, slope value, and aperture ratio) of the equal-transect oblique tunnel portal were considered in this study. The results showed that the hat oblique shape was the most efficient portal design to alleviate the pressure gradient and micro-pressure wave compared to the other designs examined in this study, and the mitigation mechanism of the hat oblique design on the initial compression wave was explained. Then the effects of the slope value and the aperture ratio of hat oblique tunnel portal on the pressure gradient and micro-pressure wave were investigated, and the parameters of the equal-transect oblique tunnel portal were optimized to alleviate the pressure gradient and micro-pressure wave induced by high-speed trains entering tunnels.

1. Introduction

The strong transient pressure and gust velocity magnitudes generated by high-speed trains passing through a tunnel may potentially create danger to the trackside workers and damage the structures of the train and tunnel (Gilbert et al., 2013; Miyachi et al., 2016; Mok and Yoo, 2001; Soper et al., 2013). According to Liu et al. (2017), strong pressure changes can be transmitted into the interior of the high-speed train through the gaps on train body, resulting in interior pressure change that can cause ear discomfort to passengers and staff. In particular, this can cause serious medical problems for people who are highly sensitive to pressure changes (Gawthorpe, 2000). The compression wave induced by a train entering a tunnel propagates to the opposite portal, where it is partly reflected into the tunnel and partly emitted outside as micro-pressure wave. The micro-pressure wave can be strong enough to produce a blast noise. The strong plosive sound with pressure levels of up to 140–150 dB can have significant impacts on the neighboring environment at the tunnel exit, and can even cause structural damages to the buildings surrounding the tunnel exit and negatively affect residents' normal lives (Aoxi et al., 1995; Fukuda et al., 2005; Uystepruyst et al., 2013). The magnitudes of the transient pressure and micro-pressure wave are mainly determined by the blockage ratio, which is defined as the ratio of the cross-sectional area of the train to that of tunnel entrance (Ito, 2000; Maeda et al., 1993; Peters, 2000). In addition, the magnitude and duration of pressure waves are also strongly linked to the temporal pressure gradient of the initial compression wave. Such temporal pressure gradient and the micro-pressure wave can be reduced by optimizing the parameters of the tunnel portal (Uystepruyst et al., 2013; Zhang et al., 2017b). However, many railway lines determine the types of trains to be operated before they are constructed. Thus, optimizing the shape of the train nose as an efficient way to alleviate train induced tunnel aerodynamics (Bellenoue and Kageyama, 2002; Kikuchi et al., 2011; Ku et al., 2010; Maeda et al., 1993; Ogawa and Fujii, 1997) is not suitable for these railway lines. Accordingly, adding tunnel portals and optimizing the parameters of the tunnel portals has become a reasonable and effective option (Howe, 1999; Howe et al., 2006; Liu et al., 2010; Réty and Grégoire, 2002; Xiang and Xue, 2010).

According to the standards proposed by Geng et al. (2006) and Zhao

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et al. (2004), tunnel portals should be designed for railway tunnels under two conditions in China. First, when there are no buildings within 50 m from the tunnel mouth and the amplitude of the micro-pressure wave is greater than 50 Pa at a distance of 20 m form the tunnel exit. The second condition was that when the amplitude of the micro-pressure wave is greater than 20 Pa at the buildings that are located within 50 m from the tunnel mouth. The micro-pressure wave value approximately correlates with the cubic of the train speed (Ozawa and Maeda, 1988; Yamamoto, 1977), which indicates that the micro-pressure wave significantly increases with the increase of the train speed. In addition, according to the study by Gilbert et al. (2013), a confined space with opening structure can reduce the train induced transient pressures effectively. Thus, tunnel portals with opening structures (slope sections and the vent holes) were widely adopted for high-speed railway lines to alleviate the transient pressure and micro-pressure wave.

The generation and propagation process of the initial compression and expansion waves can be optimized through the design of the tunnel portal to alleviate the pressure gradient and micro-pressure waves (Liu et al., 2010; Uystepruyst et al., 2013). Changing the propagation process of the pressure waves induced by train passing through a tunnel was a common way to alleviate the transient pressure and the micro-pressure wave. Propagation process of the train induced pressures in the tunnel was investigated worldwide in recent decades. Several representative scaled experimental studies based on similar experiments (Baker, 1986; Heine and Ehrenfried, 2014; Johnson, 1999; Yang et al., 2016; Zhang et al., 2017a, 2017b; Zhou et al., 2014) were carried out, and the propagation process of the pressure waves in the tunnel was introduced. Quit few of the full scale experiments have ever been carried out (Kikuchi et al., 2005; Ko et al., 2012; Liu et al., 2017), and influences of pressure propagation on pressure changes were analyzed. In addition, the results of these full scale experimental tests provide sufficient data for the validation of the scaled experimental and numerical simulation results. The rapid growth of the advanced computer technology made the numerical simulation of the train aerodynamics more effective and convenient. Computational simulation methods for train aerodynamics were proposed and perfected (Baker, 2014; Chen et al., 2017; Chu et al., 2014; Hemida and Baker, 2010; Liu et al., 2017; Niu et al., 2018; Uystepruyst et al., 2013; Zhang et al., 2017a), and the propagation of the pressures induced by train passing through tunnels was simulated and analyzed. Based on these experimental and simulation methods and the obtained pressure propagation results, the investigations on the design and parameter optimization of tunnel portal are carried out. Réty and Grégoire (2002) conducted a study bearing upon tunnel portal extensions, which attenuate the pressure gradient of the entry wavefront, and assessed the influence of various geometrical parameters relating to short, flared, or perforated tunnel portal extensions. The effect of the enlarged tunnel portal on the pressure gradient was investigated by Heine and Ehrenfried (2014), and the optimized tunnel portal can reduce the pressure gradient by 44%. Howe et al. (2003) studied the influence of an unvented tunnel entrance hood on the compression wave generated by a high-speed train. A theoretical prediction method of the initial compression wave was proposed and verified by experimental test data. The results of this study showed that the compression waves calculated by the proposed theoretical prediction method were found to be in excellent agreement with experimental test results. Subsequently, Howe et al. (2006, 2008) proposed numerical procedures to rapidly predict the compression waves generated by a high-speed train entering a tunnel with long and short vent tunnel portals and found that the prediction methods for long and short vent tunnel portals were different from each other. The two studies indicated that the length of the tunnel portal had a significant influence on the generation of the initial compression waves. In addition, according to the calculation methods proposed by Howe et al. (2006, 2008), the initial compression waves can be attenuated significantly by the vented tunnel portal compared to the unvented tunnel portal studied by Howe et al. (2003). Iida and Howe (2007) optimized the parameters of the slit-like windows set on the wall of a rectangular tunnel portal to suppress the harmful environmental impact of the compression wave generated when a high-speed train enters a long tunnel. This study results showed that, for an enlarged rectangular tunnel portal, the reduction in pressure gradient can be achieved using a slit whose width decreases inwards from the hood entrance and its total length is no more than approximately 80% of the hood length. Murray and Howe (2010) studied the influences of the cross-sectional area of tunnel portal on the compression wave and micro-pressure wave, and found that the pressure gradient can be attenuated by installing an enlarged tunnel portal to increase the initial rise time of the compression wave. It was also shown that optimizing the cross-sectional area of the enlarged tunnel portal can potentially reduce the amplitudes of the compression wave pressure gradient and micro-pressure wave. Normal tunnel portals were examined by Xiang and Xue (2010) to analyze the influence of the tunnel portal on the initial compression wave; nine different tunnel portals (with different lengths, cross-sectional areas, and ventilation holes) were compared by numerically simulating the compression waves induced by a train entering a tunnel. The results obtained by this study revealed the significant influence of the tunnel portal length, cross-sectional area, and ventilation holes on the initial compression wave, and the ventilation holes were not a symmetrically distributed to alleviate the impulsive wave. Uystepruyst et al. (2013) performed a parametric study of tunnel portals in order to reduce the pressure gradient of the compression wave generated by a high-speed train entering a tunnel. Four different designs of tunnel portals (without portal, enlarged constant section portal, conical progressive portal, and elliptic progressive portal) were primarily compared, and the results showed that the enlarged constant section portal was the most efficient design when compared to the progressive (elliptic or conical) section portal. Then, the influences of the cross-sectional area and length of the enlarged tunnel portal were investigated. The results indicated that optimizing the cross-sectional area of the enlarged constant section tunnel portal can reduce the amplitude of the pressure gradient by half, and the pressure gradient can also be reduced significantly when the length of the enlarged constant section tunnel portal is 2–8 times the train nose length.

It can be concluded from the above discussion that many studies were focused on the optimization of the constant section tunnel portal, such as the length, cross-sectional area, and parameters of the ventilation holes. However, with the development of high-speed railways, oblique tunnel portals with cross-sectional area equivalent to that of the tunnel have been widely used, as they require less space and cost than enlarged tunnel portals (Liu et al., 2010). Many studies were also conducted on the aerodynamic performances induced by trains entering tunnels with oblique tunnel portals. Mok and Yoo (2001) studied four kinds of tunnel entrance designs to investigate the formation of the compression wavefront at the tunnel entrance, and the oblique tunnel portal design was considered in this study. The results showed that the oblique tunnel portal alleviated the compression wave relatively better than the constant section tunnel portal with holes (parameters of the holes were not optimized) on the ceiling. Bellenoue et al. (2002) simulated the initial compression wave induced by a train model entering a tunnel with an oblique tunnel portal; however, this study was primarily focused on the simulation method that can be adopted to simulate the formation of the initial compression wave. The study conducted by Winslow et al. (2005) considered the slope values of the oblique tunnel portal, in which the portal model was formed "scarfed" with tapering side walls. Results indicated that optimizing the slope value of the oblique tunnel portal can potentially reduce the pressure gradient by approximately 15%; however, little or no additional improvement can be achieved with longer walls. Liu et al. (2010) conducted a study on tunnel portals optimization. In addition to examining the traditional tunnel portal designs (enlarged constant section tunnel portal, conical progressive portal, and constant section tunnel portal with holes), the oblique tunnel portals with different slope values were also considered. This study results indicated that a significant reduction in the micro-pressure wave can be achieved