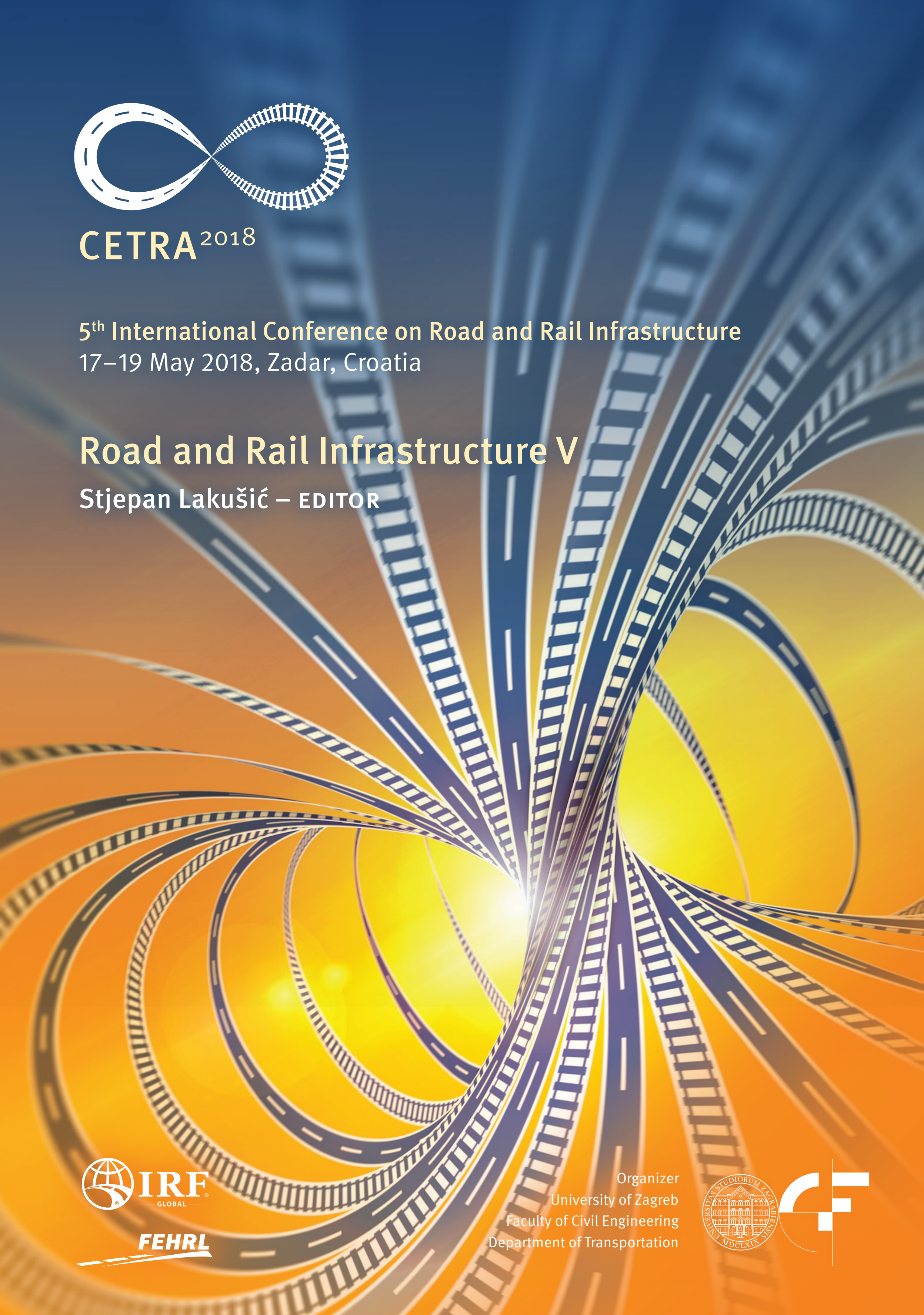

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – EDITOR

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CETRA^{2018}
5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

TITLE
Road and Rail Infrastructure V, Proceedings of the Conference CETRA 2018

EDITED BY
Stjepan Lakušić

ISSN
1848-9850

ISBN
978-953-8168-25-3

DOI
10.5592/CO/CETRA.2018

PUBLISHED BY
Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE
minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY
“Tiskara Zelina”, May 2018

COPIES
500

Zagreb, May 2018.

Proceedings of the
5th International Conference on Road and Rail Infrastructures – CETRA 2018
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A NUMERICAL STUDY ON THE EFFECT OF PRESSURE RELIEF IN A HIGH-SPEED RAILWAY TUNNEL

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Abstract

High-speed trains have been developed widely in many countries in order to transport large quantity of people and commodities rapidly. When a high speed train enters a tunnel, aerodynamic resistance is generated suddenly. This resistance causes micro pressure wave and discomfort to passengers. Therefore, it is essential to incorporate a pressure relief system in a tunnel and streamlined shape of a train in order to reduce aerodynamic resistance caused by a high-speed train. Additionally, the cross-sectional area of a tunnel should be carefully determined to reduce discomfort of passengers. A pressure relief duct and a vertical shaft are representative measures in a tunnel. This study represents the effect of pressure relief ducts integrated in a cross-passage. The pressure relief duct was integrated with a cross-passage in order to save cost and construction time. One-dimensional network numerical simulations were carried out in order to estimate the effect of pressure relief systems.

Keywords: Air pressure in a tunnel, One-dimensional network numerical analysis, Pressure change within time interval, Pressure relief duct, Aural discomfort

1 Introduction

Recently, investment for high-speed railways has been increased due to large demand on fast and secure public transportation. In addition, underground transport system, such as a high-speed train has become faster than past in order to satisfy passengers' expectations. Therefore, many construction plans for high-speed railway have been planned in many countries. South Korea also has carried forward high-speed underground transportation system in a metropolitan area. The system is called as a Great Train Express (GTX) and planned to use a high-speed train that can travel with the speed of 350 km/h. High-speed trains need a track with larger curvature than low-speed trains in order to maintain its speed. Therefore, a tunnel is one of the most important infrastructures for high-speed trains.

When a high-speed train enters a tunnel, large aerodynamic resistance is generated [2]. As the speed of a train increases, the effects of aerodynamics become important on the design of tunnels and trains. Complicated distribution of aerodynamic pressure occurs in front of a running train. The nose of a train has a streamlined shape to decrease aerodynamic resistance acting on a train [3]. However, this aerodynamic pressure on a train becomes much more complicated when a train enters a tunnel. This complicated aerodynamic pressure by a running train in a tunnel causes problems such as micro pressure wave and aural discomfort on passengers. Pressure comfort and health protection of passengers should be guaranteed according to design codes and specifications [7]. UIC 779 presents that the maximum pressure difference on passengers in a train should be less that 10 kPa [8]. Additionally, a non-pressure tight train should have a pressure difference less than 4.5 kPa for 4 seconds in a double-track railway tunnel, and 3.0 kPa for 4 seconds in a single-track tunnel. For a pressure

DOI: https://doi.org/10.5592/CO/CETRA.2018.898

tight train, a pressure difference should be lower than 1.0 kPa in a second, 1.6 kPa for 4 seconds, and 2.0 kPa for 10 seconds in either single-track or double-track tunnel [7] [8]. In South Korean standard for a railway tunnel, pressure difference in a tunnel should be lower than 800 Pa for 3 seconds when there is only one train running in a tunnel and 1,250 Pa for 3 seconds. Aerodynamic resistance developed by a train in a tunnel has a significant influence on not only aural comfort, but also traction demand required for a train passage in a tunnel [1]. When a high-speed locomotive enters a tunnel, large traction power demand is necessary due to aerodynamic pressure resistance in a tunnel [4]. The speed of train is usually decreased before the train enters a tunnel, so various measures are adopted in a tunnel not to lower the speed of a locomotive [5]. For example, the Channel Tunnel connecting United Kingdom and France adopted circular ducts with a diameter of 2 m every 250 m between two running tunnels, Figure 1. These pressure relief ducts could alleviate air pressure resistance in the Channel Tunnel and let Eurostar trains travel with the speed of 160 km/h [6]. These ducts are arch shaped in order to prevent interference with running tunnels [6]. Various numerical simulations carried out to investigate and analyze the effect of a pressure relief system in this study. The maximum pressure difference cause by a running train in a tunnel was thoroughly investigate with various scenarios.

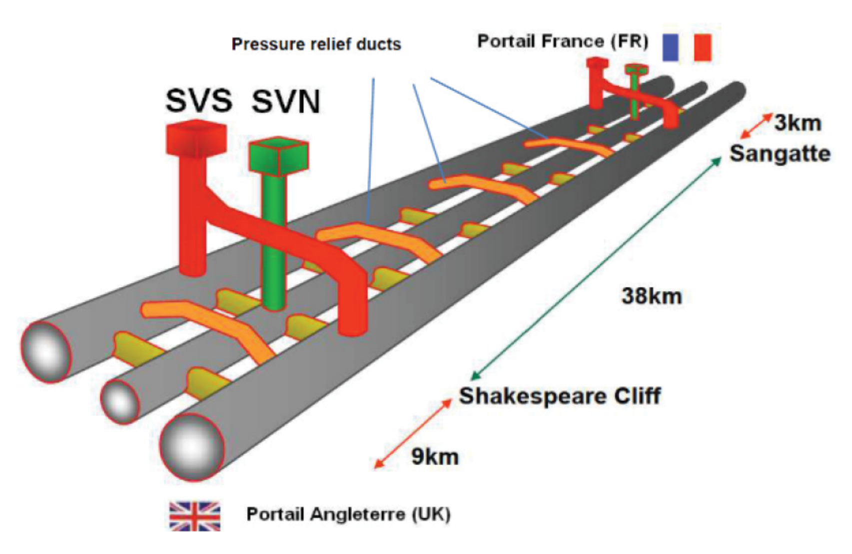

Figure 1 Pressure relief ducts installed in the Channel Tunnel

2 Aerodynamic resistance in a tunnel

Abrupt aerodynamic resistance might be developed in front of a train when it enters a tunnel [5]. A train entering a tunnel displaces air and the air pressure increases abruptly at the tunnel portal at the train nose. The overpressure pressure leads to some air flowing back alongside the train and out of the entrance of the tunnel. The remainder passes down the tunnel behind a pressure wave front. The pressure wave propagates with the speed of sound as a compression wave along the tunnel, Figure 2.

As the tail of the train enters the tunnel, a sudden pressure drop occurs behind the train. This second pressure wave also propagates with the speed of sound as a decompression wave along the tunnel. This aerodynamic resistance, or aerodynamic drag leads to a characteristic pressure distribution along the train. As the nose of a train reaches a certain point in the tunnel, a pressure drop occurs and the pressure further drops due to the longitudinal friction along the train surface. Behind the train tail the pressure increases again as shown in Figure. 3. The pattern of the pressure distribution in the tunnel continuously changes, Figure. 4.

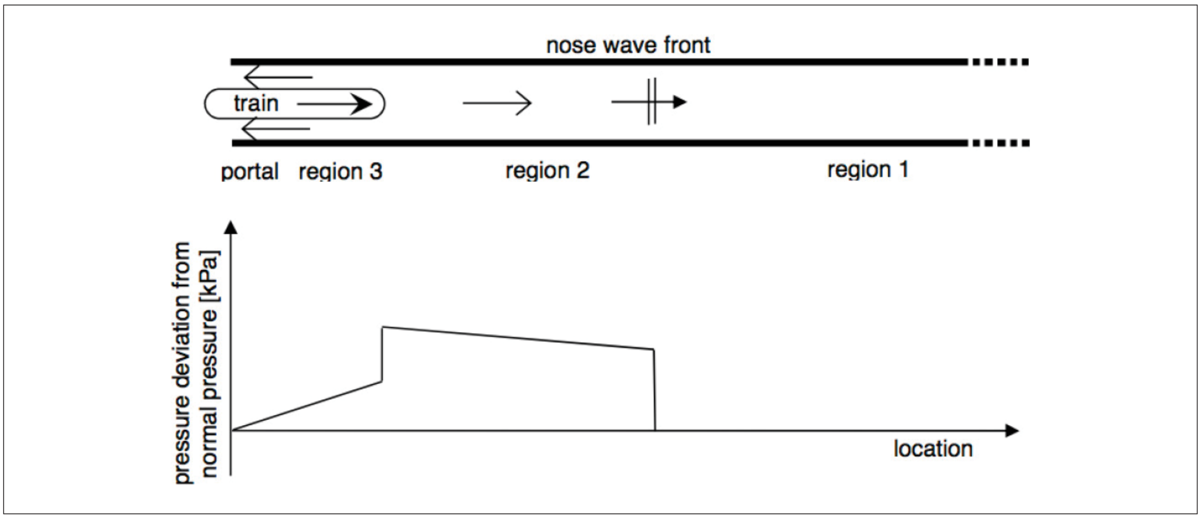

Figure 2 Pressure deviation caused by a train along tunnel(1) [5]

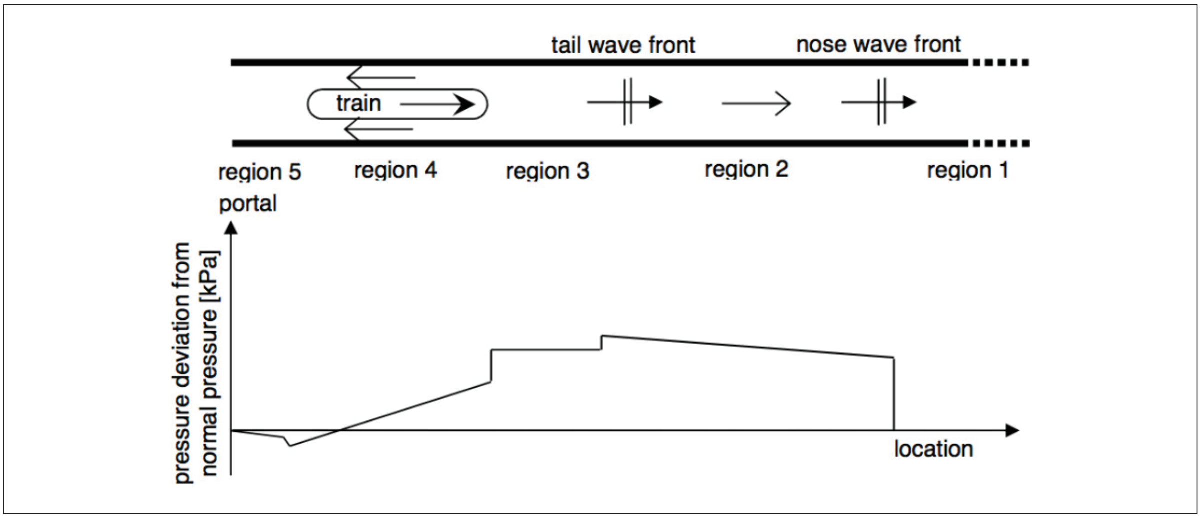

Figure 3 Pressure deviation caused by a train along tunnel(2) [5]

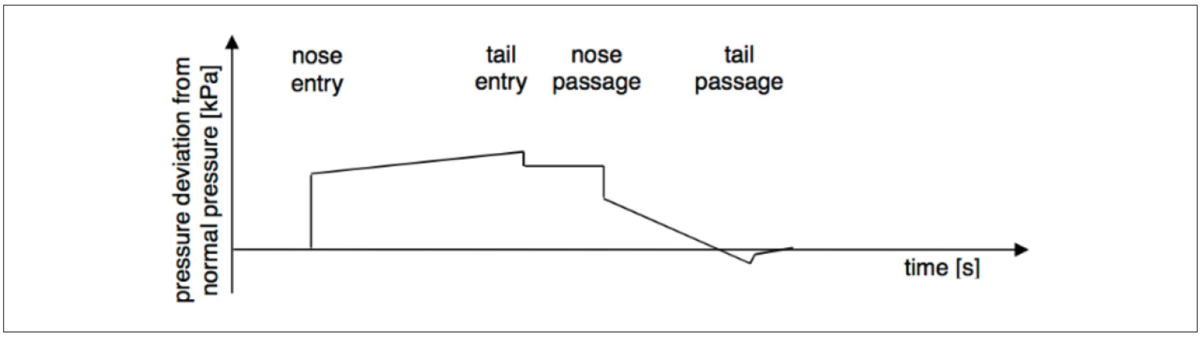

Figure 4 Pressure deviation caused by a train along tunnel(3) [5]

When the wave is reached the exit portal, it is partially reflected and travels back as an expansion wave [5]. Ends of tunnels reflect compression waves as expansion waves, and expansion waves as compression waves. An expansion wave takes in air at the end of the tunnel, and it propagates as a compression wave. Further reflections at portals, changes of free cross-sectional area of tunnels and trains might lead to various compression and expansion waves oscillating simultaneously in the tunnel. While oscillating in the tunnel, the amplitude of the waves decreases due to friction and losses due to reflection.

3 Design codes for pressure deviation in a tunnel

For high speed railway tunnels, pressure comfort is one of the most important aspect to determine the size and shape of the cross-sectional area of a tunnel. The criteria for pressure comfort are commonly defined by the maximum pressure changes within a given time period. Many countries propose design codes to determine the cross-sectional area of tunnels in terms of aural comfort to passengers. The International Union of Railway(UIC) harmonized different criteria and proposed two sets of pressure comfort criteria, such as UIC 660 [7] and UIC 779-11 [8], Table 1. UIC 779-11 proposes that the pressure change should be lower than 1.0 kPa for 1 second and 2.0 kPa for 10 seconds. However, the pressure change should be lower than 0.5 kPa for 1 second and 1.0 kPa for 10 seconds in UIC 660. This high comfort level according UIC-Code 660 was initially proposed by German Rail and implemented in their initial high-speed network [7]. The criteria were developed on the premise of "not to have complaints" about pressure comfort and to be on the safe side. In tunnels with strong gradients it turned out, however, that it was impractical to respect the 60-s-time-interval as the change in height leads to a significant pressure change already. Therefore, only the time intervals of 1, 3 and 10 s are considered. South Korea proposes pressure comfort criteria similar to UIC 660 [Table 1] and additional pressure comfort criteria for the cases when there is only one running train or two crossing trains in a tunnel [7, 8].

Table 1 Maximum pressure change(kPa) within a time interval

Time interval (seconds)	UIC 660	UIC 770-11	Korean Code
1	0.5	1.0	0.5
3	0.8	-	0.8 (one train) 1.25 (two trains)
4	-	1.6	-
10	1.0	2.0	1.0
60	2.0	-	2.0

4 Numerical simulation

4.1 Model and conditions for numerical simulation

Numerical simulations were carried out in order to analyse the pressure changes in time period in a tunnel. A numerical model was based on the preliminary design of Honam-Jeju subsea tunnel in Korea. The tunnel is a mechanically driven tunnel by TBM and has a circular cross section with area of 57.25 m^2. The tunnel is a single-tube and double track tunnel and pressure relief ducts are installed between two tunnels, Figure 5. This pressure relief duct is incorporated to decrease aerodynamic resistance in a tunnel because it is very hard to construct a vertical shaft in a subsea tunnel. The length of the tunnel in numerical simulation is 35 km and the area and distance of pressure relief ducts are assumed variously for different simulation cases. Table 2 shows parameters used in THERMOTUN, which is a numerical simulation program being widely used for design of a tunnel. THERMOTUN is developed in Dundee Tunnel Research (DTR) to analyse pressure changes in a tunnel using one-dimensional network models. The program has been widely used for many projects and validated through a lot of researches [9, 10].

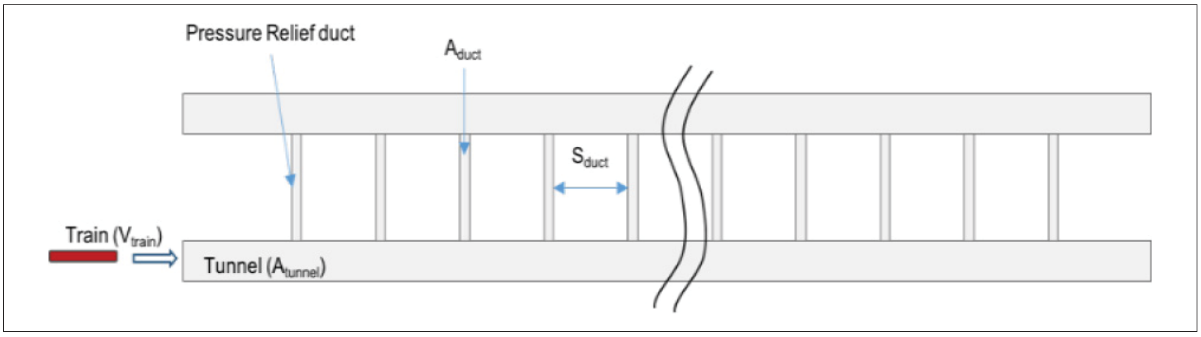

Figure 5 Schematic diagram for numerical modelling

Table 2 Parameters for numerical simulation

Parameter		**Value**
Train	Shape of head	Hypothetical
	Length	L_{train} = 201 m
	Cross-sectional area	A_{train} = 9.34 m^2
	Perimeter	P_{train} = 11.67 m
	Maximum speed	V_{train} = 350 km/h
	Time constant of pressure tightness	τ = 18 sec
	Longitudinal friction factor	f_{train} = 0.003
	Nose and tail loss coefficient	k_{nose} = 0.05, ktail = 0.07
Tunnel	Length	L_{tun} = 35,000 m
	Type	Twin tube, single track
	Cross-sectional area	A_{tun} = 60 m^2
	Perimeter	P_{tun} = 31.5 m
	Tunnel friction factor (D'arcy-Weisbach definition)	λ_{tun} = 0.024
	Tunnel friction factor	f_{tun} = 0.06
	Length of pressure relief duct	L_{rd} = 30 m
	Inclination	i = 0 %
	Ambient, tunnel temperature	15 °C
	Normal pressure at sea level	101,300 Pa

In order to investigate the effect of a pressure relief duct on pressure changes in a tunnel, 42 simulation cases were prepared. Each simulation case has a unique combination of various parameters, such as the speed of train, the cross-sectional area of a tunnel and a pressure relief duct, and the spacing between ducts as shown in Table 3. The train is assumed to run with the speed (Vtrain) of either 300 km/h or 350 km/h, because the effect of pressure relief system becomes significant in high speed railway tunnels. Currently, high speed trains in Korea, KTX, runs with the speed of 300 km/h in open tracks. The cross-sectional areas of tunnels (Atunnel) are 42.59 m^2 and 57.25 m^2. The former is the area of the Channel Tunnel and the latter is from the area of the preliminary design of Honam-Jeju subsea tunnel. The area of the cross-section of a pressure relief duct (Aduct) varies from 0.70 m^2 to 3.14 m^2. The smallest value is from the preliminary design of Honam-Jeju subsea tunnel and the 3.14 m^2 is the area of the pressure relief duct installed in the Channel Tunnel. The distance between pressure relief ducts (Sduct) varies from 250 m to 300 m to investigate the effect of pressure relief ducts on the pressure change in a tunnel. Pressure tightness of a train (τ) was set to 18 s because KTX high-speed train is manufactured with pressure tightness larger than 18 s.

Table 3 Parameters used in numerical simulations and results

Simulation case	Vtrain [km/h]	Atunnel $[m^2]$	Aduct $[m^2]$	Sduct [m]	Pressure change in time period of 1 s [kPa in s]	Pressure change in time period of 10 s [kPa in s]
1	350	42.59	0.70	250	0.284	2.071
2	350	42.59	0.70	275	0.286	2.086
3	350	42.59	0.70	300	0.288	2.098
4	350	42.59	1.00	250	0.276	2.013
5	350	42.59	1.00	275	0.278	2.027
6	350	42.59	1.00	300	0.279	2.038
7	350	42.59	2.00	250	0.262	1.917
8	350	42.59	2.00	275	0.264	1.929
9	350	42.59	2.00	300	0.265	1.938
10	350	42.59	3.14	250	0.255	1.860
11	350	42.59	3.14	275	0.256	1.873
12	350	42.59	3.14	300	0.257	1.883
13	350	57.25	0.70	250	0.193	1.421
14	350	57.25	0.70	275	0.194	1.430
15	350	57.25	0.70	300	0.195	1.437
16	350	57.25	1.00	250	0.188	1.386
17	350	57.25	1.00	275	0.189	1.394
18	350	57.25	1.00	300	0.190	1.401
19	350	57.25	2.00	250	0.180	1.326
20	350	57.25	2.00	275	0.181	1.333
21	350	57.25	2.00	300	0.181	1.340
22	350	57.25	3.14	250	0.175	1.290
23	350	57.25	3.14	275	0.176	1.296
24	350	57.25	3.14	300	0.176	1.304
25	300	42.59	0.70	250	0.176	1.490
26	300	42.59	0.70	275	0.203	1.501
27	300	42.59	0.70	300	0.206	1.512
28	300	42.59	2.00	250	0.187	1.376
29	300	42.59	2.00	275	0.189	1.385
30	300	42.59	2.00	300	0.190	1.394
31	300	57.25	0.70	250	0.139	0.984
32	300	57.25	0.70	275	0.140	0.990
33	300	57.25	0.70	300	0.141	0.997
34	300	57.25	1.00	250	0.136	0.960
35	300	57.25	1.00	275	0.137	0.965
36	300	57.25	1.00	300	0.138	0.972
37	300	57.25	2.00	250	0.130	0.917
38	300	57.25	2.00	275	0.131	0.922
39	300	57.25	2.00	300	0.131	0.927
40	300	57.25	3.14	250	0.126	0.890
41	300	57.25	3.14	275	0.127	0.895

4.2 Analysis results

Aerodynamic pressure occurred in a tunnel fluctuates as a train passes through the tunnel. Figure. 6 shows how air pressures acting on the nose, middle, and tail of a train are changed for 1 second and 10 seconds. The result in Figure. 6 is from the simulation case 1, which has a train velocity of 350 km/h, cross-sectional area of a tunnel of 42.59 m^2, cross-sectional area of a duct of 0.70 m^2, and spacing of duct of 250 m. As shown in Figure. 6, high positive normal pressure is occurred when a tunnel enters the entrance portal. This high pressure decreased quickly as the train moves in the tunnel and there is a complicated fluctuation of pressure along the tunnel. The biggest pressure change is occurred right before the train passes through the exit portal of a tunnel. Pressure changes from 42 simulation cases were listed in Table 2 and Figure. 7. In Figure. 7, red dots are values of the maximum pressure change in 10 seconds time interval and blue dots are the values in 1 second time interval. A red line and an orange line show the pressure criteria from UIC 779-11; the red line stand for 2.0 kPa in 10 seconds time interval and the orange line stand for 1 kPa in 1 second time interval. A light blue and dark blue line are from UIC 660; the light blue line stand for 1 kPa in 10 seconds time interval and the dark blue line stand for 0.5 kPa in 1 second time interval. As clearly shown in Figure. 7 and Table 2, pressure changes in a tunnel are influenced by various aspects, such as the velocity of a train, the cross-sectional area of a tunnel and a pressure relief duct and spacing between ducts. Every simulation case could meet the criteria for 1 second time interval according to both UIC 779-11 and UIC 660. However, some simulation cases could not meet the criteria for 10 second time interval.

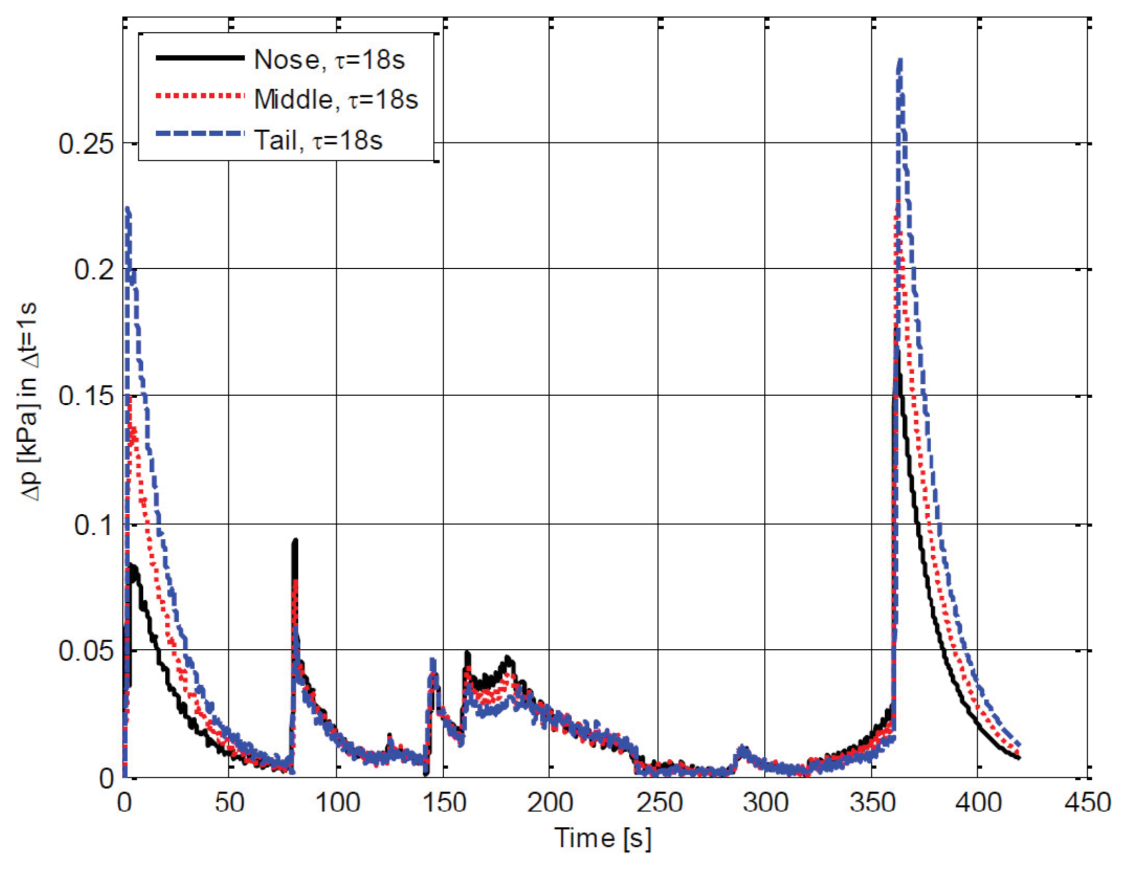

Figure 6 Pressure change in time period of 1 s and 10 s (case 1)

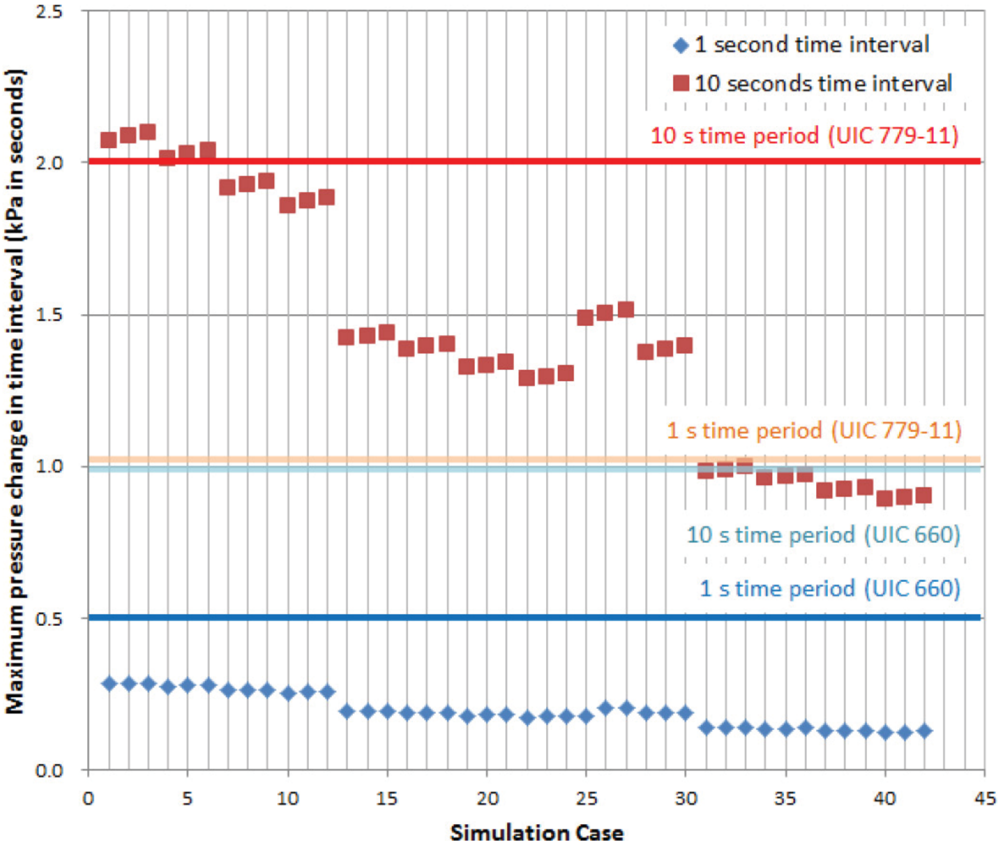

Figure 7 Pressure change in time period of 1 s and 10 s

From the case no. 1 to case no. 12 simulate that a high-speed train runs with the speed of 350 km/h in a tunnel, which has the same cross-sectional area to the Channel Tunnel. These 12 simulation cases shows very high pressure changes for 10 seconds time interval through train passage. When the cross-sectional area of a pressure relief duct is 0.7 m^2 (from case 1 to case 3) and 1.0 m^2 (from case 4 to case 6), the maximum pressure change exceed 2.0 kPa in 10 seconds time interval (UIC 779-11) and 1.0 kPa in 10 seconds (UIC 660). As the cross-sectional area of a duct is increased to 2.0 m^2 and 3.14 m^2 (from case 4 to case 6), the maximum pressure changes are smaller than 2.0 kPa, but much higher than 1.0 kPa, which is a standard for 10 seconds time interval in UIC 660. This implies that the cross-sectional area of a pressure relief duct should be larger than 2.0 m^2 in order to meet the minimum criteria of UIC 779-11.

The preliminary design of Honam-Jeju subsea tunnel has a larger cross-sectional area with 57.25 m^2 (from case 13 to 24). As the cross-sectional area of a tunnel increased from 42.59 m^2 to 57.25 m^2, pressure changes could be decreased around 28 – 31 % and satisfy the 10 seconds time interval criterion of UIC 779-11. However, every simulation cases with the area of 57. 25 m^2 showed pressure changes larger than 1.0 kPa in 10 seconds time period. This implies that passengers in a high-speed train running 350 km/h may suffer pressure discomfort. Therefore, it is required to adopt other measures to decrease the maximum pressure change caused by a train in a tunnel.

The speed of a train is decreased to 300 km/h in other 18 simulation cases (from case 25 to case 42). When a train runs with 300 km/h in a tunnel with 42.59 m^2, the maximum pressure change in 10 seconds time interval decreased 28 % compared to the cases with the speed of 350 km/h. However, the pressure change in 10 seconds time interval ranges from 1.376 kPa to 1.512 kPa, and they are much higher than the values from UIC 660 (from case 25 to case 30). Therefore, it is necessary to increase the area of a tunnel in order to make the pressure change lower than 1.0 kPa in 10 seconds time interval (UIC 660). From the simulation case 31 to 42, a train runs with the speed of 300 km/h in a tunnel with a cross-sectional area of 57.25 m^2. When the cross-sectional area of a duct is 0.7 m^2 and the spacing of ducts is 250 m, the maximum pressure change is 0.984 kPa in 10 seconds time interval and it satisfies 10 seconds standard of UIC 660. As the spacing of ducts increases, the maximum pressure change decreases slightly. In addition, the pressure change can be also decreased with increasing cross-sectional area of a pressure relief duct. Therefore, it is obvious that the area of a tunnel should be larger than 57.25 m^2 and pressure relief ducts with cross-sectional area larger than 0.7 m^2 should be installed with the spacing smaller than 300 m when a high-speed train runs with the maximum speed of 300 km/h to satisfy UIC 779-11 and UIC 660 standards.

5 Conclusion

A one-dimensional numerical simulation using THERMOTUN was carried out in order to select the optimal area of a tunnel and investigate the effect of pressure relief ducts installed between two running tunnels. The pressure change occurred in a tunnel is one of the most important factor for designing the cross-sectional area of a tunnel. Therefore, a detailed 42 numerical analysis were conducted with various train speed, cross-sectional area of a tunnel and a pressure relief duct, and spacing between ducts. According to the results of numerical analysis, the optimum combination of a tunnel and a duct was proposed for a high-speed railway tunnel which a locomotive can run with the speed of 300 km/h. The specifications of a tunnel and a duct from this research could meet the standard for the maximum pressure change in a tunnel according to UIC 779-11 and UIC 660. The results from this study can be summarized as follows.

Pressure changes in time interval of 1 second and 10 seconds becomes significantly different according to the speed of a locomotive, cross-sectional area of a tunnel and a pressure relief duct, and spacing between ducts. All of 42 simulation cases could satisfy the criteria for the pressure change in 1 second time interval of both UIC 779-11 and UIC 660. There are some simulation cases which could not meet the 10 seconds criteria of UIC 660 when a train runs with 350 km/h. Even though the speed of a train is decreased to 300 km/h, the maximum pressure change in 10 seconds is higher than 1.0 kPa when the cross-sectional area of a tunnel is 42.59 m^2. Therefore, it is necessary to increase the area of a tunnel to 57.25 m^2 in order to lower the maximum pressure change in the tunnel.

If a high-speed locomotive runs with 350 km/h in the Channel Tunnel, which has a cross-sectional area of 49.25 m^2, the maximum pressure change becomes larger than 2 kPa in 10 seconds time interval. If a pressure relief ducts with the cross-sectional area of 3.14 m^2 were installed every 250 m, the maximum pressure change in 10 seconds can be lower that the criteria of UIC 779-11. However, it highly surpasses the 10 seconds criteria of UIC 660 and passengers in a train may feel aural discomfort in a tunnel. This implies that a high-speed locomotive will not be able to run faster than 300 km/h in the Channel Tunnel. A tunnel with larger area (57.25 m^2) can have much lower pressure changes compared to the Channel Tunnel. However, the speed of train should be restricted to 300 km/h in order to meet UIC 660 criteria for pressure comfort.

Acknowledgements

This research was supported by a grant (Project number: 15SCIP-B066321-06 (Development of Key Subsea Tunnelling Technology)) from Infrastructure and Transportation Technology Promotion Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

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