The aerodynamic effect of air-shafts in the single track tunnel with small cross sectional area on conventional line

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Summary

Purpose of the present is to investigate air-shaft configurations in a single track tunnel for reducing pressure fluctuations and micro pressure wave that is generated according to train speeds. Three main configurations were examined for equally spaced air-shafts with small bore. Experiments were performed with a 1/6 scale moving model rig for the tunnel of 0.764 km length and the train of 4 cars 1 unit. Tunnels are also for small cross-sectional area of 28 m² on conventional line in Korea. The test facility for train-tunnel systems was recently enlarged to have the test section possible in reduced scale for 1 km length tunnel. The main characteristics of the present facility with air-gun type are that the train model is guided on an one-wire system from the compressed air launcher to the absorber parts of test facility. The wire guidance hole is at the axial center of a train model. In the present test rig, after the train model was launched, the air jet generated by the driver did not enter to the tunnel model inside.

According to the result, the maximum pressure fluctuation is reduced by 4.7% for 19 equally spaced shafts with 2.135 m diameter in full-scale dimension. This result has the speed-up effect of about 33.4 km/h for the train running in a tunnel. According to the result, the micro-pressure waves radiating towards the surroundings from the tunnel exit, the maximum value of micro pressure wave is reduced by 34% for 5 equally spaced shafts and reduced by 48.1% for 10 equally spaced shafts.

Keywords
Air-shafts, tunnel, experiments, pressure fluctuations, micro pressure wave, moving model rig
1 Introduction

When a train enters to a tunnel as high speed, the passengers of cabin experience an ear-discomfort as the effect of the pressure fluctuations induced by a train entry. A countermeasure for reducing the pressure fluctuations is to install air-shafts in tunnel as convenient and cost-down solution without enlarging the bore [Vardy, 1976 and Burri, 1997].

Currently on Korean conventional line, the tunnels consisted of 5% of 445.5 km total length on Seoul-Pusan line and 3% of 256.3 km total length on Seoul-Mokpo line. The curve radius of these lines is small, and the number of tunnels are not many because these low-speed lines were constructed before 1960 years. But, upon the network plan of new branch line for the speed-up operation to 180 km/h, tunnels will be more increased up to 10% ~ 30%. For the purpose of speed-up on conventional line, we could consider that the adoption of the tilting train and the construction of new line possible to enlarge the curvature of railway line.

It is well known that the cost of tunnel construction is more diminished when the cross-sectional areas of tunnel is more smaller [UIC-code 779-11, 1995]. In the addition of the optimum bore design considered the countermeasures of ear-discomfort for passengers in tunnel on high-speed railroad line, the tunnel which applied air-shafts is more effective for reducing the ear-discomfort of passengers. This method of aerodynamic design minimize the cost of construction by means of the mechanical machine to penetrate easily of small bore [Henson, 1997].

In the present study, the moving model rig of 1:61 reduced scale possible to test up to the tunnel of 1 km length in full scale was redeveloped recently with more extended specifications as shown in Figure 1. This test rig has been used for countermeasure developments for reducing the micro-pressure wave in tunnel of high-speed railway [Kim, 1999]. With this test rig, we showed the speed-up effects of about 33.4 km/h for single-track tunnel of small bore applied 19 air-shafts at the inner side wall. This result is the same effect that it is more enlarged 50% for the cross-sectional area of tunnel. Also according to the result for the micro-pressure waves radiating towards the surroundings from the tunnel exit, the maximum value of micro pressure wave is reduced by 84% for 5 equally spaced shafts and reduced by 81.8% for 10 equally spaced shafts.

![Diagram of moving model rig](image.png)

**Figure1** The schematic of moving model rig
Figure 2 The tunnel with small cross-sectional area on conventional line

Figure 3 “Saemaul” train on conventional line

Table 1 Specifications of tunnel and train (full scale dimensions)

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>“Saemaul” train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track</td>
<td>Single</td>
</tr>
<tr>
<td>Cross-sectional area</td>
<td>28 m²</td>
</tr>
<tr>
<td>Perimeter</td>
<td>21.17 m</td>
</tr>
<tr>
<td>Length</td>
<td>764 m</td>
</tr>
<tr>
<td>Configuration</td>
<td>4 car 1 unit</td>
</tr>
<tr>
<td>Cross-sectional area</td>
<td>9.8 m²</td>
</tr>
<tr>
<td>Perimeter</td>
<td>12.08 m</td>
</tr>
<tr>
<td>Overall length</td>
<td>94.3 m</td>
</tr>
</tbody>
</table>

2 The Test Model of Railway Tunnel and Vehicle

The cross-sectional areas of the single-track tunnels on conventional line range from 24 m² to 29.4 m². Daegu-Pusan route of Seoul-Pusan conventional line consists of many tunnels. In the near future, on this railway high-speed train will be operated during about 6 years. Therefore, for the most of tunnels with small cross-sectional area, these tunnels should be reconstructed as the cross-sectional area of optimum space owing to the pantograph of train and aerial wiring in the tunnel. In the present study we investigate the air-shaft configuration in a single track tunnel of small cross-sectional area for reducing pressure fluctuations and micro pressure wave that is generated according to train speeds.
Figure 4  Axis-symmetric transformation for "Saemaul" train (full scale dimension)

Figure 5  Schematic of moving model experiment
The experiments were carried out using the moving model rig with 1/61 reduced scale. Since the train model in test facility travels through tunnel with the real speed and with the same condition of blockage ratio for train to tunnel in full scale, the pressure waves generate as real dimension in tunnel [Wolff, 1997].

The length of tunnel with the vertical type air-shafts was 12.522 m (full scale; 764 m) and the length of train model is 1.546 m (full scale; 94.3 m). Figure 6 shows the front view of tunnel model with air shafts. The tunnel model and the train model are shown in Table 1, Figure 5 and Figure 6. The “Saemaul” train was used because the train operates as maximum speed of 140 km/h on conventional line in Korea. In tunnel, “Saemaul” train operates as a maximum speed of about 100 km/h. Figure 7 is a photograph of experimental set-up. The “Saemaul” train operates as an axisymmetric shape, the effective radius variation and the effective area variation of the rose part along the axial distance are shown in Figure 4 (a) and (b). The train model of present study has one unit of four cars as a target of moving model test. In the next work, the study for the length effect of train will be necessary to introduce properly.
3 Test Conditions and Measurement Systems

The most of tunnels on Korean conventional line were constructed before 1960 years. Owing to lining maintenance in tunnels over 40 years, the surface roughness of tunnel inside has become larger. The tunnel with the rock surface without lining also existed. Then, if average surface roughness $\epsilon_p$ of these tunnels with ballast track is estimated to be 6 mm, Relative roughness $\epsilon_p/D_p$ is $1.005 \times 10^{-3}$. As the necessary conditions of perfect similarity have to satisfy the relative roughness $\epsilon_p/D_p = \epsilon_m/D_m$ [Gerhart, 1985], surface roughness in 1/61 reduced scale become to $9.836 \times 10^{-5}$ m as indicated in Table 2. But this surface roughness is very small value, so we coated the wall surface of tunnel inside with vinyl tape and polished surface of aluminum for the external of train model. On the other hand, the ballast track in tunnel model was adapted with only surface roughness of wood plate and without porosities of ballast layer.

The experiments were carried out using moving model rig redeveloped the tunnel model of 1 km length in full scale as shown in Figure 1. The main characteristics of the present facility with air-gun type that the train model is guided on an one-wire system from the compressed air launcher to the shock absorber parts of test facility. The wire guidance hole is at the axial center of a train model. After the train model was launched, the air jet generated by the driver did not enter to the tunnel model inside.

In Figure 5, Pressure transients are measured at five locations using Endevco 8510B-1 pressure transducers. Micro pressure waves were measured with sound level meter of Rion XN-12A for ultra-low frequency range. The measurement microphone for micro pressure wave was located at 0.333 m distance for angle 45° from center of tunnel exit and it was positioned at 20 mm upward from ground. Photo sensors in the front of tunnel model triggered the start of test and, at the same time, measured the train speed. Photo sensors were located each other at 700 mm distance from the front and the end of tunnel model and measured independently the speed of train to calculate the deceleration of train speed. The analog signals passed through a low pass filter at 1 kHz before being sampled at 100 kHz by an analogue to digital converter. The details of experiment with moving model rig have been published in reference [Kim, 2001].

4 Experimental Results

Development for tunnel system with air-shafts was experimented for reducing the air-pressure fluctuations in tunnel according to number of air-shafts. Above all, in the case of not applying air-shafts in tunnel, Figure 8 show that the measurement result of pressure transients in reduced scale compared with numerical results in full scale by using the characteristic equations. These curves are the pressure fluctuations of air in tunnel inside and for train speed 149 km/h. Train speed is an entry speed at tunnel entrance. The locations of measurement 15 m and 8.090 min reduced scale. The measurement results show very good agreement with numerical predictions.
Figure 8  Comparison of measurement and numerical results for train entry speed km/h in the case without air-shaft.

(a) $x_p = 1.115 \text{ m}$  \hspace{2cm} (b) $x_p = 8.090 \text{ m}$
We specified a reference position for first shaft that is located a distance of 333.33 mm (full scale; 20.33 m) from tunnel entrance. The groups of the equally spaced shafts from this position were three kinds and we performed parameter study for number of shafts.

For the first case, Intervals between continuous shafts were 2666.66 mm (full scale; 162.67 m) and total numbers were 5 for equally spaced shafts. For the second case, Intervals between continuous shafts were 1333.33 mm (full scale; 81.33 m) and total numbers were 10 for equally spaced shafts as shown in Figure 7. For the third case, Intervals between continuous shafts were 666.66 mm (full scale; 40.67 m) and total numbers were 19 for equally spaced shafts. Internal diameters of shafts installed in tunnel were 35 mm (full scale; 2.14 m) and were taken as the same size for the all case. The height of all shafts was selected 340 mm (full scale; 20.74 m) as shown in Figure 6; this height could be converted as 295 mm (full scale; 18 m) for height from ceiling of tunnel inside to surface ground of mountain. Except for "Sung-Hyun" tunnel in Seoul-Pusan conventional line, this height corresponded to average height of 14 tunnels. We measured the pressure transients in tunnel and micro-pressure wave on tunnel exit for ranges of train entry speeds as 110 km/h ~ 178 km/h.
In Figure 9 ~ Figure 14, experiment results of pressure transients is represented for positions of pressure transducers. For positions of transducers $x_p$, the peak values of the first generated compressive waves by train entry decrease with increasing number of air-shafts. Also, on transducer positions, after train passage, the peak values of compressive and expansive waves decrease so much during time advance until the position of tunnel exit. From Figure 9 ~ Figure 14, it would indicate that the strength of reflected waves on both tunnel ends considerably by means of aerodynamic damping effect of equally spaced air-shafts. Therefore, it seems that the pressure waves with weak strength run cross in tunnel. From these experimental results, it is suggested that the maximum peak values of pressure fluctuations decrease with increasing number of continuous air-shafts and the reduction effects for maximum peak values of
pressure fluctuations increase with decreasing of train entry speeds in tunnel. The lower the train speed is, the higher the reduction effects of air-shafts for pressure fluctuations will be.

In Table 3 ~ Table 5, these results include more experimental data summarized from Table 3 ~ Table 5, in the case of same speeds of train at tunnel entrance and in case when number of air-shafts become twice in the tunnel, the reduction effects for maximum peak values of pressure fluctuations increase by about 10%. For our experimental speed ranges of train model, in the case that number of air-shafts are 19 at one side wall of tunnel, the reduction effects of pressure fluctuations in tunnel reaches the ranges of 37.4% ~ 44.7%. Through this parametric study as applying 19 air-shafts in conventional railway tunnel with small cross-sectional area of 7565 mm² (full scale; 28 m²), it could be possible to introduce the speed-up effect of about 33.4 km/h for train operation, that is, the enlarged effect of 50% in cross-sectional area of tunnel.

**Table 3** The reduction effect of pressure fluctuations in tunnel with air-shafts for train entry speed 10 km/h

<table>
<thead>
<tr>
<th>Conditions</th>
<th>1.115 m</th>
<th>3.910 m</th>
<th>8.090 m</th>
<th>10.48 m</th>
<th>12.257 m</th>
<th>Max. peak values</th>
<th>Reduction effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without air-shaft</td>
<td>961 Pa</td>
<td>1034 Pa</td>
<td>864 Pa</td>
<td>712 Pa</td>
<td>335 Pa</td>
<td>1034 Pa</td>
<td>Reference</td>
</tr>
<tr>
<td>5 air-shafts</td>
<td>741 Pa</td>
<td>591 Pa</td>
<td>471 Pa</td>
<td>423 Pa</td>
<td>219 Pa</td>
<td>741 Pa</td>
<td>28.3%</td>
</tr>
<tr>
<td>10 air-shafts</td>
<td>668 Pa</td>
<td>544 Pa</td>
<td>379 Pa</td>
<td>313 Pa</td>
<td>165 Pa</td>
<td>668 Pa</td>
<td>35.4%</td>
</tr>
<tr>
<td>19 air-shafts</td>
<td>576 Pa</td>
<td>382 Pa</td>
<td>258 Pa</td>
<td>241 Pa</td>
<td>170 Pa</td>
<td>572 Pa</td>
<td>44.7%</td>
</tr>
</tbody>
</table>

**Table 4** The reduction effect of pressure fluctuations in tunnel with air-shafts for train entry speed 48 km/h

<table>
<thead>
<tr>
<th>Conditions</th>
<th>1.115 m</th>
<th>3.910 m</th>
<th>8.090 m</th>
<th>10.48 m</th>
<th>12.257 m</th>
<th>Max. peak values</th>
<th>Reduction effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without air-shaft</td>
<td>1640 Pa</td>
<td>1823 Pa</td>
<td>1596 Pa</td>
<td>1323 Pa</td>
<td>732 Pa</td>
<td>1823 Pa</td>
<td>Reference</td>
</tr>
<tr>
<td>5 air-shafts</td>
<td>1434 Pa</td>
<td>1070 Pa</td>
<td>867 Pa</td>
<td>801 Pa</td>
<td>505 Pa</td>
<td>1434 Pa</td>
<td>21.3%</td>
</tr>
<tr>
<td>10 air-shafts</td>
<td>1232 Pa</td>
<td>998 Pa</td>
<td>887 Pa</td>
<td>808 Pa</td>
<td>569 Pa</td>
<td>1232 Pa</td>
<td>32.4%</td>
</tr>
<tr>
<td>19 air-shafts</td>
<td>1049 Pa</td>
<td>738 Pa</td>
<td>691 Pa</td>
<td>651 Pa</td>
<td>516 Pa</td>
<td>1049 Pa</td>
<td>42.5%</td>
</tr>
</tbody>
</table>

**Table 5** The reduction effect of pressure fluctuations in tunnel with air-shafts for train entry speed 78 km/h
Figure 15  The intensities of micro-pressure waves in the case of installing air-shaft tunnel

Maximum value of micro pressure wave is related to train speed as represented in literature [Ozawa, 1988]. We could use more brief equation for clear comparisons of characteristics about micro pressure wave even in the conditions of various blockage ratios [Kim, 1999].

\[ P_{\text{max}} = \tilde{A} \cdot \frac{U^3}{10^6} \]  \hfill (1)
where $P_{\text{max}}$ is maximum value of micro pressure wave, $R$ is the reduction factor for micro pressure wave in the given ranges of train speed $U$ and train entry speed (km/h) at tunnel entrance.

### Table 6 The comparison of reduction effects for micro-pressure wave with air-shafts

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Ranges of Train entry speed</th>
<th>Reduction factor $R$</th>
<th>Reduction effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without air-shaft</td>
<td>100 km/h ~ 240 km/h</td>
<td>4.86</td>
<td>Reference</td>
</tr>
<tr>
<td>5 air-shafts</td>
<td>100 km/h ~ 200 km/h</td>
<td>3.20</td>
<td>34.2 %</td>
</tr>
<tr>
<td>10 air-shafts</td>
<td>100 km/h ~ 200 km/h</td>
<td>2.52</td>
<td>48.1 %</td>
</tr>
</tbody>
</table>

In Figure 15, the intensities of micro-pressure waves were represented for the case of installing air-shafts in tunnel. The empirical curves of solid line were obtained by using equation (1) from experimental data, and then the values of reduction factors were determined. As for the experimental results of air-shafts, we could not represent the measured values because the time dependent radiations of micro pressure waves were very small signal within range of random noise. These test results are summarized in Table 6. From Table 6, according to the results for micro-pressure waves radiating towards the surroundings from the tunnel exit, the maximum value of micro-pressure wave is reduced by 34.2% for 5 equally spaced shafts and reduced by 48.1% for 10 equally spaced shafts. In case when number of air-shafts become twice in the tunnel, the reduction effects for maximum peak values of micro-pressure wave increase by about 14%.

### 5 Conclusions

A difficult problem for achieving speed-up on conventional railway line is the ear-discomfort phenomena by pressure fluctuations in tunnel. In the present study, the moving model rig of the 1:61 reduced-scale of tunnelling air-shafts are installed for single track tunnel of the small cross-sectional area in order to reduce the pressure fluctuations and micro pressure waves in tunnel. It would be proposed an alternative among the various speed-up methods. In the condition of the same air-shaft diameter, we carried out the 1:61 reduced scale experiment for the train entry speeds of 110 km/h ~ 178 km/h and applying such that number of air-shafts vary from zero to nineteen in tunnel of 0.764 km length. Three main configurations were examined for equally spaced air-shafts with small bore. So, we obtained the following results for reducing the pressure fluctuations and micro pressure wave.

1. Maximum peak values of pressure fluctuations in tunnel decrease with increasing of equally spaced air-shafts, and the reduction effects of these maximum peak values increase with the lower speed of train.
2. In the case of same speeds of train in tunnel entrance and when number of air-shafts become twice in tunnel of same length, the reduction effects for maximum peak values of pressure fluctuations increase by about 10%.
3. For our experimental ranges of train launching speeds such as 110 km/h ~ 178 km/h, in the case that the number of air-shafts at one side wall of tunnel are 19, the reduction effects of pressure fluctuations in tunnel reaches the ranges of 37.4% ~ 44.7%.
(4) Also, according to the results for the micro-pressure waves radiating towards the surroundings from the tunnel, the maximum value of micro pressure wave is reduced by 34% for 5 equally spaced shafts and reduced by 81% for 10 equally spaced shafts.

Through this parametric study applying 19 air-shafts in conventional railway tunnel with small cross-sectional area of 28 m², it could be possible to introduce the speed-up effect of about 33.4 km/h for train operation, that is, the enlarged effect of 50% in cross-sectional area of tunnel.

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