Small Model Experiment on the Pressure Wave Propagation from Train Entrance in Conventional Line Tunnel Having a Station or Signal Crossing Station

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When a high-speed train enters a tunnel, compression wave is generated in front of the train. This compression wave propagates in the tunnel at the sound velocity. In recent years, the running speed of train is advancing with the improvement of vehicle technology, and the problem of the tunnel pressure wave may occur for the conventional limited express. However, there are a few research reports on the tunnel pressure waves for conventional express. This paper deals with tunnel pressure increase and pressure gradient propagating from tunnel entrance, using the apparatus with diaphragmless acceleration driver acceleration and small train models of limited express in short tunnel with station and crossing station models.

1. INTRODUCTION

When a high-speed train enters a tunnel, compression wave is formed in front of the train. This compression wave propagates in the tunnel at the sound velocity. When the pressure wave arrives at the tunnel exit, it is reflected back into the tunnel as an expansion wave, and simultaneously a pulsed pressure wave, called “tunnel micro-pressure wave”, is radiated from the exit toward the surrounding area. This micro-pressure wave generates strong noise and vibration, which cause environmental problems specially in today’s Shinkansen. Several studies on the wave propagation in tunnels caused by the Shinkansen have been performed in past years\(^1,2\). The micro-pressure wave is closely related to the pressure gradient of the compression wave arriving at the tunnel exit. Therefore, the problems of formation and propagation of the pressure wave have been studied, and it is clarified that improvement in the train nose geometry\(^3\) and installation of the tunnel entrance-hood\(^4,5\) are the effective means to reduce the micro-pressure wave. However, it is still necessary to have the data of the pressure wave behavior for Shinkansen lines with further increase of train speed up to 320km/h.

Besides these micro-pressure wave problems in Shinkansen, the problem of tunnel pressure wave has also occurred in conventional limited express, as recent improvement of vehicle performance is so great that the running speed of conventional train is rapidly increasing. In some conventional lines newly established, the ratio of the train cross-sectional area of train to tunnel is much larger than that of the Shinkansen as shown in Table 1. Consequently, in conventional lines as well as Shinkansen, the pressure wave formation and propagation in tunnel often produce the problems\(^6\). Especially, in the case of high-speed train which runs into the long slab track tunnel, the aerodynamic and pressure wave problems appear significantly.

Until now, however, for the existing railways we have not obtained clear solution. In the study of tunnel pressure wave formation and propagation, there are a few research reports on the conventional lines\(^6,7\), where the train speed is ranged from 100 to 160 km/h. Therefore, in this study we focus on the
running speed of limited express as 130 – 160 km/h, and we have performed small-scale experiments with two-types of axi-symmetric train models based on the cross-sectional area of the conventional train. This paper deals with the pressure wave formation and propagation phenomena near tunnel entrance by these experiments using an apparatus with diaphragmless gas driver acceleration system, and small train nose models of limited express, combined with a short tunnel, station model and signal crossing station model. We have obtained pressure waveform data and compared them with different train speed and nose geometry. In this study we have also performed experiments as both station and signal crossing station in the tunnel, which can be seen in “Hokuhoku line”.

![Fig.1 Mechanism of tunnel micro-pressure wave](image)

2. BACKGROUND

2.1 TUNNEL MICRO-PRESSURE WAVE PROBLEM AND SOLUTIONS IN SHINKANSEN

A schematic diagram of the generating mechanism of the tunnel micro-pressure wave is shown in Fig.1. First, compression wave is generated in front of a high speed train when the train enters a tunnel. Secondly, this compression wave propagates in the tunnel at sound velocity. If the compression wave propagates in a long tunnel, the wave is deformed by several factors. In the propagation process the amplitude itself of the compression wave is attenuated by dissipating effects of tunnel track and wall. Furthermore, slab track tunnel increases rapidly the pressure wavefront steepness on nonlinear effect of the wave, while ballast track tunnel attenuates the pressure wave on energy dissipation. Thus the derivative of the pressure wavefront called “pressure gradient”, is steepened due to the nonlinear effect. Especially, it appears prominently in a long slab track tunnel. This compression wave is reflected when it arrives at the tunnel exit. The reflected wave is an expansion wave which returns into the tunnel towards the entrance. At the same time an impulsive wave is radiated to the surrounding area. This impulsive wave is called a “micro-pressure wave”.

With an increase in the running speed of the Shinkansen, many aerodynamic problems, for example, noise from pantograph, and pulsed noise from the tunnel exit called “tunnel micro-pressure wave”, have been observed. It is found that the tunnel micro-pressure wave causes significant environmental problems. Hence, the clarification of its mechanism and the solution of the problems have been mainly conducted. According to the survey results, the amplitude of micro-pressure wave is proportional to the third power of the train speed, and it is inversely proportional to radius of the tunnel. Furthermore, the micro-pressure wave is closely related to the pressure gradient (\(\partial p/\partial t\)) of the compression wave arriving at the tunnel exit. Therefore, the gradual change of train nose geometry is one of the effective means to reduce the micro-pressure wave. The other effecting way is installation of a tunnel entrance hood and a madreporic plate. These solutions have enabled us to obtain Shinkansen speed up to 300km/h with the minimized environmental influence.
Table 1  Train and tunnel cross-sectional area

<table>
<thead>
<tr>
<th></th>
<th>Shinkansen*</th>
<th>Streamline**</th>
<th>Gangway**</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{tr}$</td>
<td>12.1</td>
<td>11.3</td>
<td>11.9</td>
</tr>
<tr>
<td>$A_{tun}$</td>
<td>63.4</td>
<td>23.7</td>
<td></td>
</tr>
<tr>
<td>$R_t(A_{tr}/A_{tun})$</td>
<td>0.191</td>
<td>0.477</td>
<td>0.502</td>
</tr>
<tr>
<td>$U_{max}$ [km/h]</td>
<td>270</td>
<td>160</td>
<td></td>
</tr>
</tbody>
</table>

*: Full scale Series N700, Tokaido Shinkansen  
**: Full scale Series 683 of Hakutaka, Hokuoku Line

2.2 TUNNEL PRESSURE WAVE PROBLEM IN THE CONVENTIONAL LINE

The problems of the tunnel micro-pressure wave in Shinkansen have been studied by Railway Technical Research Institute\(^{(1) - (3)}\), several Japanese universities\(^{(10), (11)}\) and also European researchers\(^{(12)}\). Meanwhile, the problem of “tunnel pressure wave” is also to be observed by the limited express in the conventional lines, because the running speed has been improved with recent railway technological advancement. For instance, the limited express “Hakutaka” in the Hokuhoku Line (in Niigata Prefecture) is one of the fastest conventional train in Japan which can travel at 160km/h. This line has a single slab-track railway, and also has long length and small tunnel cross-sectional area. Hence, the pressure wave in the tunnel becomes a problem when a limited express train enters in or runs through the tunnel. The data of these trains and tunnel cross-sectional areas are shown in Table 1, where $A_{tr}$ is maximum value of train cross-sectional area. The running speed of the limited express is slower than the Shinkansen, however if we take a look on the ratio of the train cross-sectional area to the tunnel cross-sectional area, $R_t$ the $R_t$ of the Hokuhoku Line is twice larger than that of the Shinkansen, because the $A_{tun}$ of the Hokuhoku Line is smaller than half of the Shinkansen. This is because the Shinkansen line has double tracks, while the Hokuhoku Line has some single track tunnels.

In addition, there is a relation between pressure increase and $U$, $R_t$ and $M_{tr}$ as shown by the following Equation (1). Pressure increase $\Delta p_{c,ent}$ in the tunnel entrance\(^{(8)}\) is expressed as

$$\Delta p_{c,ent} = \frac{1}{2} \rho_0 U^2 \frac{1 - (1 - R_t)^2}{M_{tr} (1 - M_{tr})}$$  \hspace{1cm} \text{(1)}$$

where $\rho_0$ is air density[kg/m$^3$], $U$ is train speed[m/s] and $M_{tr}$ is Mach number of train. With the parameter of train speed, this relation is presented as the curves of $\Delta p_c$ and $U$ as shown in Fig.2. From this figure $\Delta p_c$ is susceptible to $U$ and $R_t$ variation for high-speed train.

![Fig. 2  $R_t\Delta p_c$ diagram](image-url)
3. EXPERIMENTAL SETUP

3.1 EXPERIMENTAL TRAIN MODELS

In this study we focused on the limited express “Hakutaka” of Hokuho Line from conventional lines. The currently-modeled train is the Series 683 express. This train has two kinds of nose geometry. One is a streamline-shaped nose which is called “Streamline-type”. The other is a train nose with gangway door which is called “Gangway-type”. In the experiments we used the train models of both geometries based on the shapes of these train noses.

First, we calculated the frontal projected area $A_{f}$ at each point of longitudinal axis, and the cross-sectional ratio of the train to the maximum area, $A_{f}/A_{f,max}$ based on the vehicle drawing of Series 683\textsuperscript{13}. The subscript $tr$ is the value at an arbitrary point and $tr,max$ is the maximum value. Secondly, after we converted the project areas into circular areas, we calculated radius ratio $r_{tr}/r_{tr,max}$ from areas of circle at each point. A graph of calculated results is shown in Fig.3. The horizontal axis is the distance from the top of the train, and the vertical axis is radius and cross-sectional areas ratio, $r_{tr}/r_{tr,max}$ and $A_{f}/A_{f,max}$. Finally, the axi-symmetric train models were fabricated and made of polyethylene with $R_{t}$ in the Table1 and $r_{tr}/r_{tr,max}$ in Fig.3. The designed model scale is 1/125. The fabricated train model noses are shown in Fig.4. The circular tunnel model was made based on the designed train models. We needed only cross-sectional change of the limited express “Hakutaka”, however we did not have to make train shape in detail, for example, pantograph and wiper. Because the pressure wave can be considered plane wave of low-frequency component\textsuperscript{16}.

![Fig. 3](#)

(a) 683Streamline-type
(b) 683Gangway-type

Fig. 3 Distribution of $A_{f}/A_{f,max}$ and $r_{tr}/r_{tr,max}$

![Fig. 4](#)

(a) 683Streamline-type
(b) 683Gangway-type

Fig. 4 Image of train models

3.2 EXPERIMENTAL APPARATUS

In this experiment we focused on the initial stage of pressure wave formation and propagation when the train model entering into a tunnel model. The experimental apparatus is shown in Fig.5. A tunnel model diameter ratio is 1/125 of the size of real scale tunnel diameter. The length of tunnel model is 55.9 times the diameter of the tunnel model. We used an original gas acceleration device with diaphragmless high pressure driver section. The train model is accelerated by high pressure gas from the driver, the frontal part of the train nose enters the tunnel model nose, and the compression wave is formed. After that train model is forcibly stopped at the stopper. The tunnel model is made of a steel pipe covered with concrete for reduction of noise by the pipe vibration. The pressure transducers are installed at $x/d_{sun} = 9.1, 35.0$ and $49.1$ from a tunnel entrance, where the formed pressure wave propagating in the tunnel model is measured by these pressure transducers. The train speed is calculated from the time duration by the model passing through the two laser beams. The aluminum film is also installed before the tunnel entrance. It prevents driven air to enter into tunnel caused by train model acceleration.

We obtained pressure waveform data and compared them with nose geometry difference and train
speed. The speed conditions of the experiment for Series 683 express are around 130 and 160 km/h. The condition of the dynamic similarity is satisfied by the conformity of the Mach number between the model experiment and the full-scale, while the Reynolds numbers are very different from each other. However, in this case, Reynolds number is possible to disregard, because we cover only pressure wave transformation in these experiments²).

In addition to the model experiment into the straight tunnel, we investigate the influence of the cross-sectional area change, by inserting an station model as shown in Fig.6(a) and a signal crossing station [SCS] model, as shown in (b). The (a) modeled Misashima station in Hokuho line and the (b) modeled Akakura SCS in Hokuho line. The pressure transducers are installed at \(x/d_{un} = 9.0, 35.0\) and 49.1. The pressure transducer at these station models is installed at \(x/d_{un} = 35.0\), the cross-sectional area of the station model is 1.39 times larger than the tunnel model, the SCS model is 2.61 times larger than the tunnel model. In this experiment the total length of tunnel-station model is also kept \(x/d_{un} = 55.9\). In this study we obtained pressure waveform data under many conditions, and compared the pressure wave propagation by installation of station models.

![Experimental apparatus](image)

4. EXPERIMENTAL RESULTS

4.1 CONSTANT \(A_{lr}\) MODEL EXPERIMENT

The waveform data are shown in Fig.7 when the Gangway-type train model entering the tunnel model at 130 km/h, pressure waveform as shown in (a), and \(x-t\) diagram as shown in (b). The horizontal axis is the elapsed time \(\Delta t\) from the trigger signal, and the vertical axis is pressure increase \(\Delta p\). The origin of horizontal axis is the trigger signal point, because trigger signal point is about the same as tunnel entrance. Measuring positions \(x/d_{un}\) are 9.1, 35.0 and 49.1. We made a mark on characteristic point, where \(a\) is point of first maximum pressure increase, \(b\) is starting point of pressure dropping, \(c\) is minimum pressure point and \(d\) is maximum pressure point. Then lines drawn to connect these points can be used to calculate the propagation speed \(V\) in Fig.7(b). Propagation speed of the wavefront \(V_1\) is 350 m/s. This wave is not shock wave but strong pressure wave because the pressure wave propagates nearly
at the sound velocity. In addition, we found that point $d$ is reflected when $c$ arrives at tunnel model exit. The pressure wavefront with various driving conditions are shown in Fig. 8. Measuring position is $x/d_{num} = 9.1$ for these data. In this figure $a$ indicates maximum pressure increase point, solid line corresponds pressure gradient, lozenge mark is average value of eight experiments error-bar is standard deviation of those experiments. Maximum pressure increase $\Delta p$ is 1.21 kPa in Fig. 8(a) when the Gangway-type train model entering the tunnel model at 130 km/h, and these values are almost equal to the reported value when Shinkansen enters the double-track tunnel at 250 km/h $^{15}$. The increase of the train speed from 130 to 160 km/h for the same Gangway-type train model produces about twice greater values of $\Delta p$ and pressure gradient $(\partial p/\partial t)_{max}$. This result is shown in (b). In addition, changing the model train nose geometry has the significant effects on the pressure wave formation as shown in (a) and (c). Comparison of pressure increase $\Delta p_c$ between theory and experiments is shown in Table 2. These data indicate the significance of the train nose shape.

(a) Pressure waveform
(b) $x$-$t$ diagram
Fig. 7  Pressure waveform (Train model: Gangway-type, Train speed: 130 km/h)

(a) Gangway-type, 130km/h
(b) Gangway-type, 160km/h
(c) Streamline-type, 160km/h
Fig. 8  Pressure waveform

Table 2  Comparison of pressure increase $\Delta p_c$

<table>
<thead>
<tr>
<th>$R_c$</th>
<th>Streamline</th>
<th>Gangway</th>
<th>Shinkansen</th>
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<tr>
<td>$\Delta p_c$</td>
<td>Exp.</td>
<td>Eq.(1)</td>
<td>Exp.</td>
</tr>
<tr>
<td>0.477</td>
<td>130</td>
<td>0.91</td>
<td>1.68</td>
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<tr>
<td></td>
<td>160</td>
<td>1.22</td>
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<td></td>
<td>275</td>
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<td>6.61</td>
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<td></td>
<td>305</td>
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<td>8.01</td>
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4.2 STATION AND SIGNAL CROSSING STATION MODEL EXPERIMENT

Furthermore, we installed a station or a signal crossing station model in the middle of the tunnel model to investigate the influence of the tunnel cross-sectional area change. The pressure change of produced wavefront with the station model is shown in Fig.9 when the train speed is 130 km/h and the train nose geometry is Gangway-type. $\Delta p$ and $(\partial p/\partial t)_{\text{max}}$ are attenuated inside the station model. One reason for attenuation of $\Delta p$ and $(\partial p/\partial t)_{\text{max}}$ is simple change of tunnel cross-sectional area. In addition, the other reason is reflection of pressure wave at station model entrance. The decrease of $\Delta p$ from entrance to station model is 27.0%. However, we found pressure gradient restoration at exit side can be found. The change of produced pressure wavefront with the SCS model is also shown in Fig.10 when the train speed is 130 km/h and the train nose geometry is Gangway-type. As the results of Fig.10, attenuation of $\Delta p$ and $(\partial p/\partial t)_{\text{max}}$ are the larger in these experiments. The decrease of $\Delta p$ from the entrance to the station model is 56.2%. In addition, the pressure is significantly attenuated inside the station model, and pressure shape is restored at exit side. These results agree with our past study, Streamline-type train model experiment (6). As the results of Fig.9 and 10, installation of a station models decreases the pressure increase of the wavefront when propagating in the tunnel.

![Figure 9](image1)
(a) $x/d_{\text{tun}} = 9.1$
(b) $x/d_{\text{tun}} = 35.0$
(c) $x/d_{\text{tun}} = 49.1$

Fig. 9 Pressure wavefront with station model (130km/h, Gangway-type)

![Figure 10](image2)
(a) $x/d_{\text{tun}} = 9.1$
(b) $x/d_{\text{tun}} = 35.0$
(c) $x/d_{\text{tun}} = 49.1$

Fig. 10 Pressure wavefront with SCS model (130km/h, Gangway-type)

5. CONCLUSION

In this paper we have focused on a limited express “Hakutaka” in the Hokusoku line in connection with tunnel pressure wave problems reported in limited express. Experimental studies using model trains and tunnel, tunnel/station or tunnel/SCS model have been performed, where we have obtained the pressure waveform data and compared them with train speed and nose geometry difference. As a result, changing of driving condition has significant effects on the pressure wave formation, while that little effects in short length propagation process. However, installation of a station models attenuates of the $\Delta p$ and $(\partial p/\partial t)_{\text{max}}$ of the wavefront propagating inside the station models. It is found that by increasing the
area of tunnel 1.39 time of origin area we can reduce the pressure increase \( \Delta p \) to almost one-quarter of its original pressure increase, and by increasing the area of tunnel 2.61 time of origin area we can reduce the pressure increase \( \Delta p \) to almost half of its original pressure increase.

REFERENCES

12) B. Auvity, M. Belloneou, T. Kageyama, “Experimental study of the unsteady aerodynamic field outside a tunnel during a train entry”, Experiments in Fluids 30 No.2 (2001), pp.221-228.