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MICRO-PRESSURE WAVES RADIATING FROM A TUNNEL PORTAL AND THEIR MITIGATION

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ABSTRACT
When a train enters a tunnel at a high speed, a compression wave is generated and propagated through the tunnel at the speed of sound. At the tunnel exit, the greater part of the compression wave is reflected, which generates a pressure variation in the tunnel and gives aural discomfort to passengers, while some part of the compression wave radiates out of the tunnel exit as a pressure pulse, which causes an explosive sound and strikes windows and doors of houses with a noisy thud in the vicinity of the tunnel portal. This pressure pulse is called a micro-pressure wave or a tunnel sonic boom. Some countermeasures are applied to the Shinkansen tunnels and trains. The typical countermeasures for the tunnel and the train are a tunnel entrance hood and the optimizing of the train nose respectively.

1 - INTRODUCTION
In 1975, trial runs on the newly-extended Okayama-Hakata section of San'yo Shinkansen line resulted in protests from residents living along the railway line because an explosive sound was generated and windows of houses were rattled near the portal of a long tunnel with slab track when a Shinkansen train entered the tunnel. This environmental problem had not occurred before near a tunnel with ballast track on Tokyo-Okayama section of the Tokaido and San'yo Shinkansen lines [1]. These phenomena are caused by a pressure pulse radiating from the tunnel portal when a compression wave generated by the train entering the tunnel is propagated through the tunnel at the speed of sound and arrives at the tunnel portal. This pressure pulse is called a micro-pressure wave or a tunnel sonic boom. The peak value of the micro-pressure wave is nearly proportional to the pressure gradient of the wave-front of the compression wave arriving at the tunnel exit and is inversely proportional to the distance from the tunnel exit. The principle of the countermeasures for mitigating the micro-pressure waves is to reduce the pressure gradient of the wave-front of the compression wave arriving at the tunnel exit. The micro-pressure waves are classified into low frequency environmental problems because the pressure pulse includes low frequency components. The environmental quality standards or the guidelines covering micro-pressure waves have not been issued in Japan.
The characteristics of the micro-pressure waves and the countermeasures for mitigating them are described.

2 - CHARACTERISTICS OF MICRO-PRESSURE WAVES
The phenomena of micro-pressure waves have three phases: the generation of the compression wave at the tunnel portal which train enters, the propagation of the compression wave through the tunnel and the radiation of the micro-pressure waves from the tunnel portal.

2.1 - Generation of compression wave by train
The pressure gradient of the wave-front of the compression wave generated by the train entering the tunnel at the tunnel entrance depend on the cross-sectional area of the train, the cross-sectional area of the tunnel, the shape of the train nose, the shape of the tunnel entrance and the train speed. The

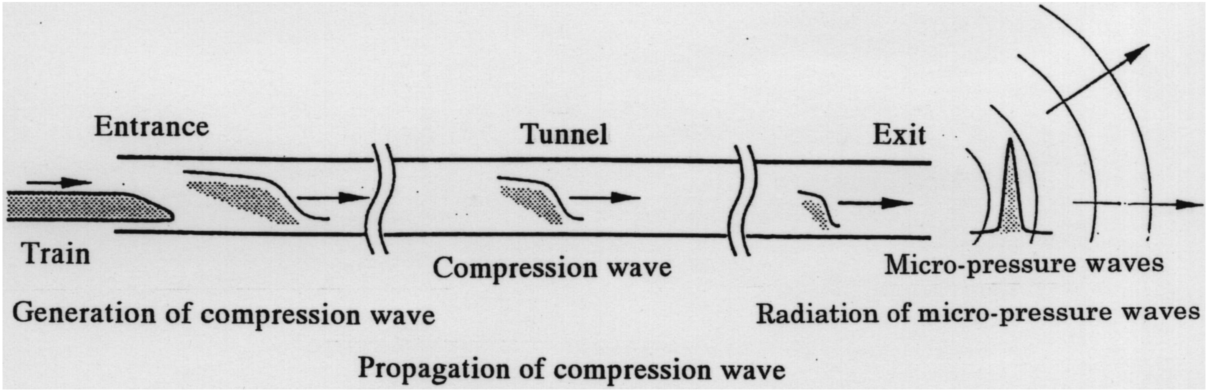

Figure 1: Phenomena of micro-pressure waves.

maximum pressure gradient of the wave-front of the compression wave $(\Delta P/\Delta t)_{\mathrm{MAX}}$ is expressed by the following equation using the pressure rise ΔP derived by Hara [2] and the time interval for pressure rise $\Delta t\,(=\kappa d/V)$.

$$\left(\frac{\Delta P}{\Delta t}\right)_{\mathrm{MAX}} = \frac{1}{2}\frac{\rho V^3}{\kappa d}\frac{1-(1-R)^2}{\left(1-\dfrac{V}{c}\right)\left\{\dfrac{V}{c}+(1-R)^2\right\}} \cdots\cdots \quad (1)$$

where V: train speed, R: cross-sectional area ratio of the train to the tunnel, c: speed of sound, ρ: density of air d: tunnel hydraulic diameter, κ: coefficient indicating the effect of the shapes of the train nose and the tunnel entrance on Δt. The equation (1) shows that the maximum pressure gradient of the wave-front $(\Delta P/\Delta t)_{\mathrm{MAX}}$ is nearly proportional to the third power of the train speed and reduces more as the cross-sectional area ratio of the train to the tunnel R becomes smaller and the coefficient κ increases more, namely the length of the nose becomes longer.

2.2 - Propagation of compression wave through tunnel

The compression wave generated by the train at the tunnel entrance is propagated through the tunnel at the speed of sound. During propagation, the compression wave is affected by the structure inside the tunnel; track, branches, etc. In the long tunnel, the wave form of the compression wave changes during propagation. The wave-front of the compression wave steepens in the tunnel with slab track by the non-linear effect of the compression wave (Fig. 2) while the wave-front of the compression wave attenuates in the tunnel with ballast track because the effect of porous material of ballast is more dominant than the non-linear effect of the compression wave (Fig. 3).

In a short tunnel where the distortion of the wave form of the compression wave is small, the wave form of the compression wave arriving at the tunnel exit is as nearly same as that at the tunnel entrance and the pressure gradient of the wave-front of the compression wave arriving at the tunnel exit is nearly proportional to the third power of the train speed. However, the pressure gradient of the compression wave arriving at the tunnel exit in the long tunnel with slab track exceeds the third power of the train speed while that in the long tunnel with ballast track becomes smaller than that in the short tunnel.

2.3 - Radiation of micro-pressure wave from tunnel exit

The relation between the compression wave arriving at the tunnel exit and the micro-pressure waves radiating from the tunnel exit is evaluated by Yamamoto [3] using the low frequency and far-field approximations.

$$p\,(r,t) = \frac{2A}{\Omega c r}\left[\frac{dP}{dt}\right]_{t-\frac{r}{c}} \cdots\cdots \quad (2)$$

where A: cross-sectional area of the tunnel and Ω: the solid angle subtended at the tunnel exit by the external flow space. The equation (2) means that the micro-pressure waves are proportional to the pressure gradient of the compression wave arriving at the tunnel exit and inversely proportional to the distance from the tunnel exit provided that the low frequency and far-field approximation are satisfied. The solid angle Ω is small when the tunnel exit is connected to a cutting section and large when the tunnel exit is connected to a elevated viaduct section. Figure 4 shows the wave forms of the micro-pressure waves and the compression waves arriving at the tunnel exit. Figure 5 shows the relation between the

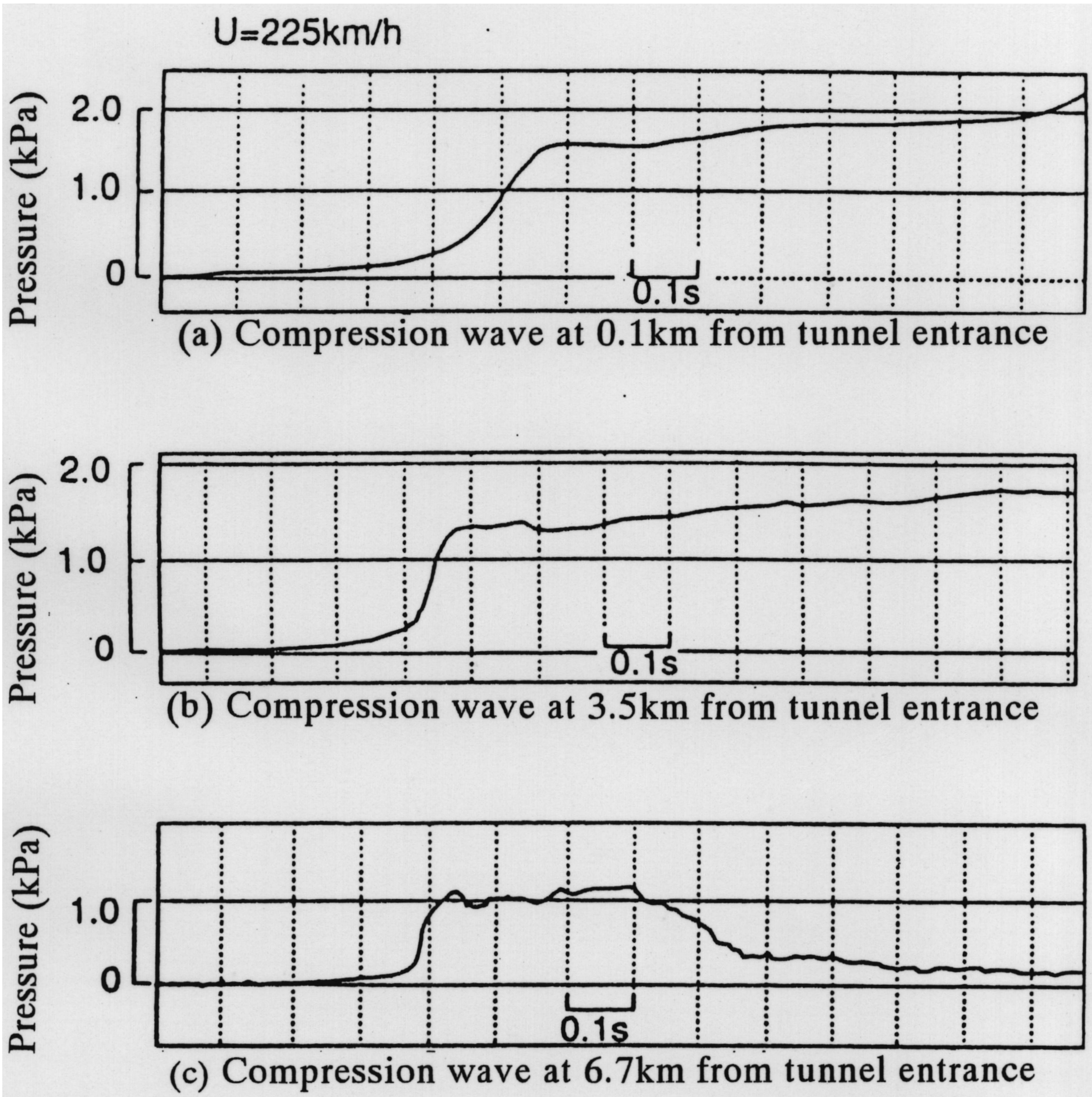

Figure 2: Deformation of compression wave in Shinkansen tunnel with slab track.

peak value of the micro-pressure waves and the train speed. In short tunnels, the peak values of the micro-pressure waves are nearly proportional to the third power of the train speed irrespective to the types of track. In the long tunnel with slab track, the peak value of the micro-pressure waves exceeds the third power of the train speed while in the long tunnel with ballast track, that is smaller than that in the short tunnels.
As the train speed increases more and the steepening of the wave-front of the compression wave arriving at the tunnel exit becomes larger, characteristics of the micro-pressure waves become more different from those in low frequency and far-field approximations. The relation between the compression wave arriving at the tunnel exit and the micro-pressure waves in this case is derived by Ozawa [1].

3 - COUTERMEASURES FOR MITIGATING MICRO-PRESSURE WAVES

The principle of the countermeasures for mitigating the micro-pressure waves is to reduce the pressure gradient of the wave-front of the compression wave arriving at the tunnel exit. The methods applied to Shinkansen tunnels are as follows: (1) the installation of a tunnel hood at the tunnel entrance, (2) the use of side branches in the tunnel and (3) the installation of a shelter with slits between two adjacent tunnels. The methods applied to the Shinkansen train are as follows: (1) the reduction of the cross-sectional area of the train and (2) the optimizing of the train nose.

3.1 - Tunnel hood

The tunnel hood has the effect of reducing the pressure gradient of the wave-front of the compression wave at the tunnel entrance. The typical tunnel hood has the cross-section about 1.4 times as large as that of the tunnel itself and has openings in the sides. The optimum area and the optimum position of the openings are decided by model experiments. Figure 6 shows the 49 m long tunnel hood. The effect of the tunnel hood depends on the length of the hood provided that the tunnel hood has the optimum openings (Fig. 7). Figure 8 shows the effect of the 49 m long tunnel hood. The micro-pressure wave decreases from about 300 Pa to 20 Pa at the train speed 250 km/h and the explosive sound disappears [4]. At present, 175 tunnel hoods are installed in Shinkansen.

3.2 - Optimizing of train nose

The model experiments were made to investigate the effect of the shape of the train nose on the wave form of the compression wave [5]. As the results, the longer nose is more effective in reducing the pressure gradient of the compression wave and the small linear variation of the cross-sectional area of the nose except the end of the nose is optimum (Fig. 9). At present, numerical simulation method has been developed by Iida [6] to find the optimum distribution of the cross-sectional area of the nose. Recent new Shinkansen trains: series 500 of JR West (Fig. 10), series 700 of JR Central and JR West and series from E1 till E4 of JR East, have the nose shape which mitigates the micro-pressure wave.

4 - CONCLUSIONS

When a train enters a long tunnel with slab track at a high speed, the micro-pressure waves radiate from the tunnel portal and generate an environmental problem. To realize the speed up of the train and the environment-friendly railway, the countermeasures for mitigating the micro-pressure waves are needed.

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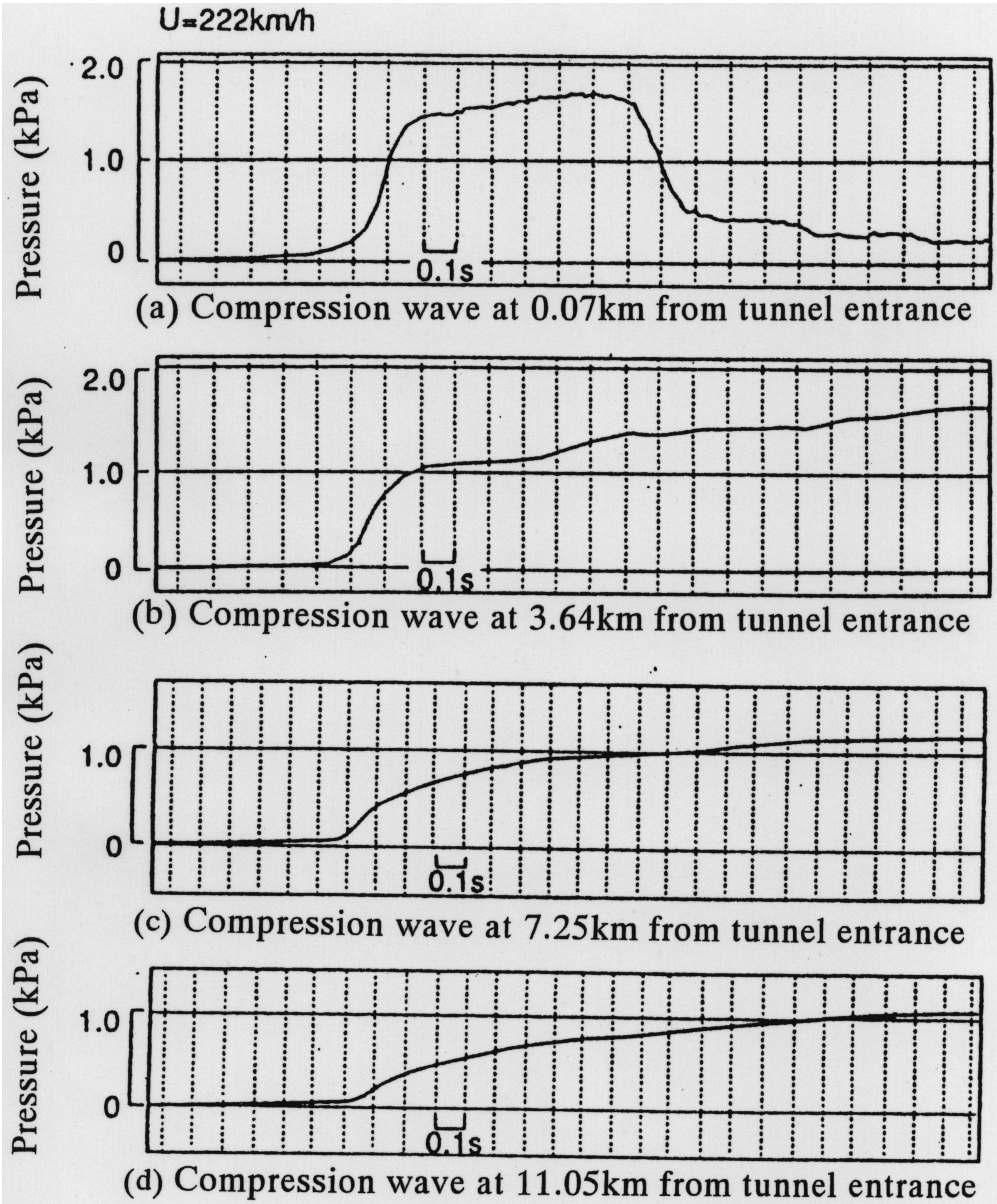

Figure 3: Deformation of compression wave in Shinkansen tunnel with ballast track.

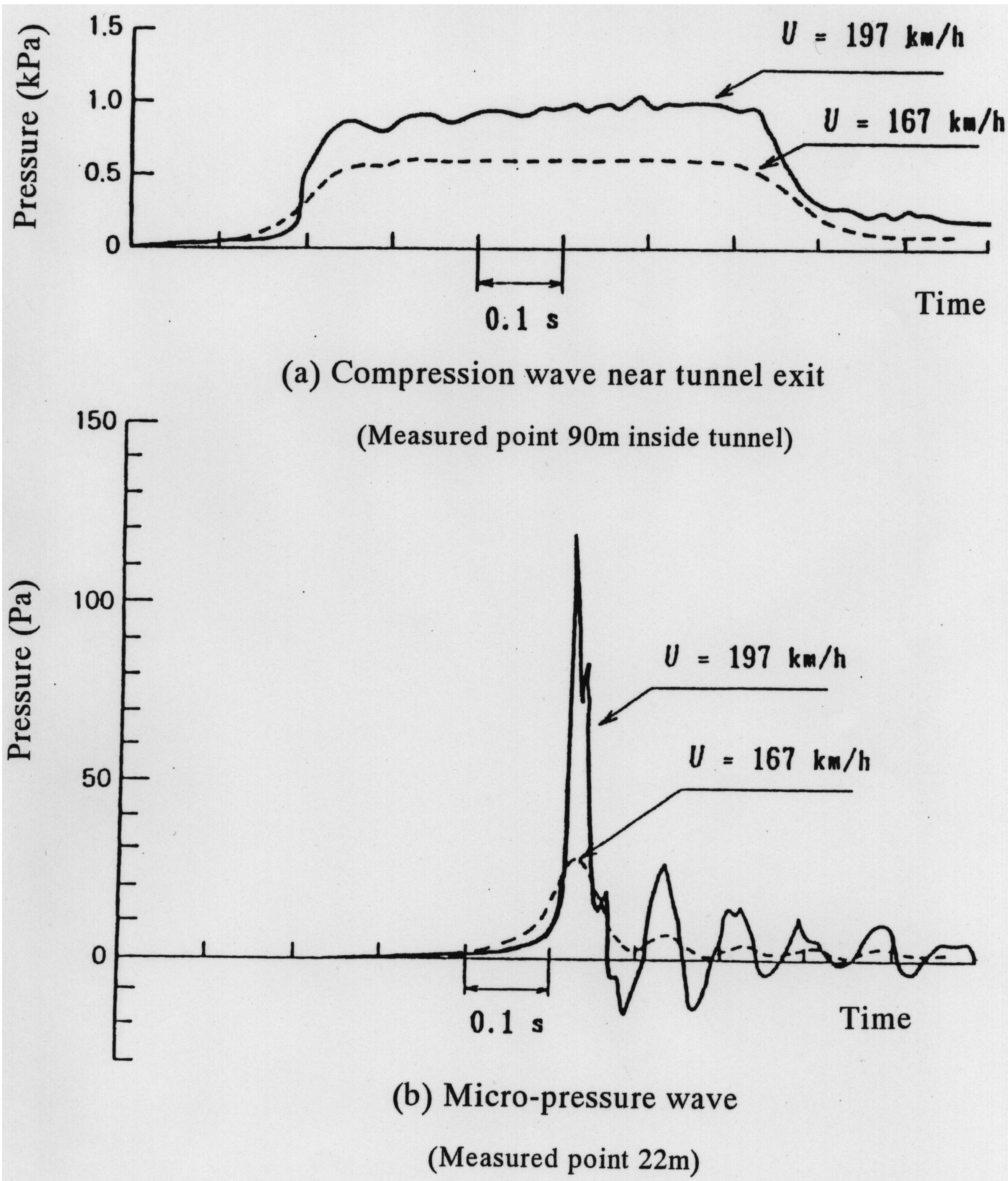

Figure 4: Compression waves at tunnel exit and micro-pressure waves.

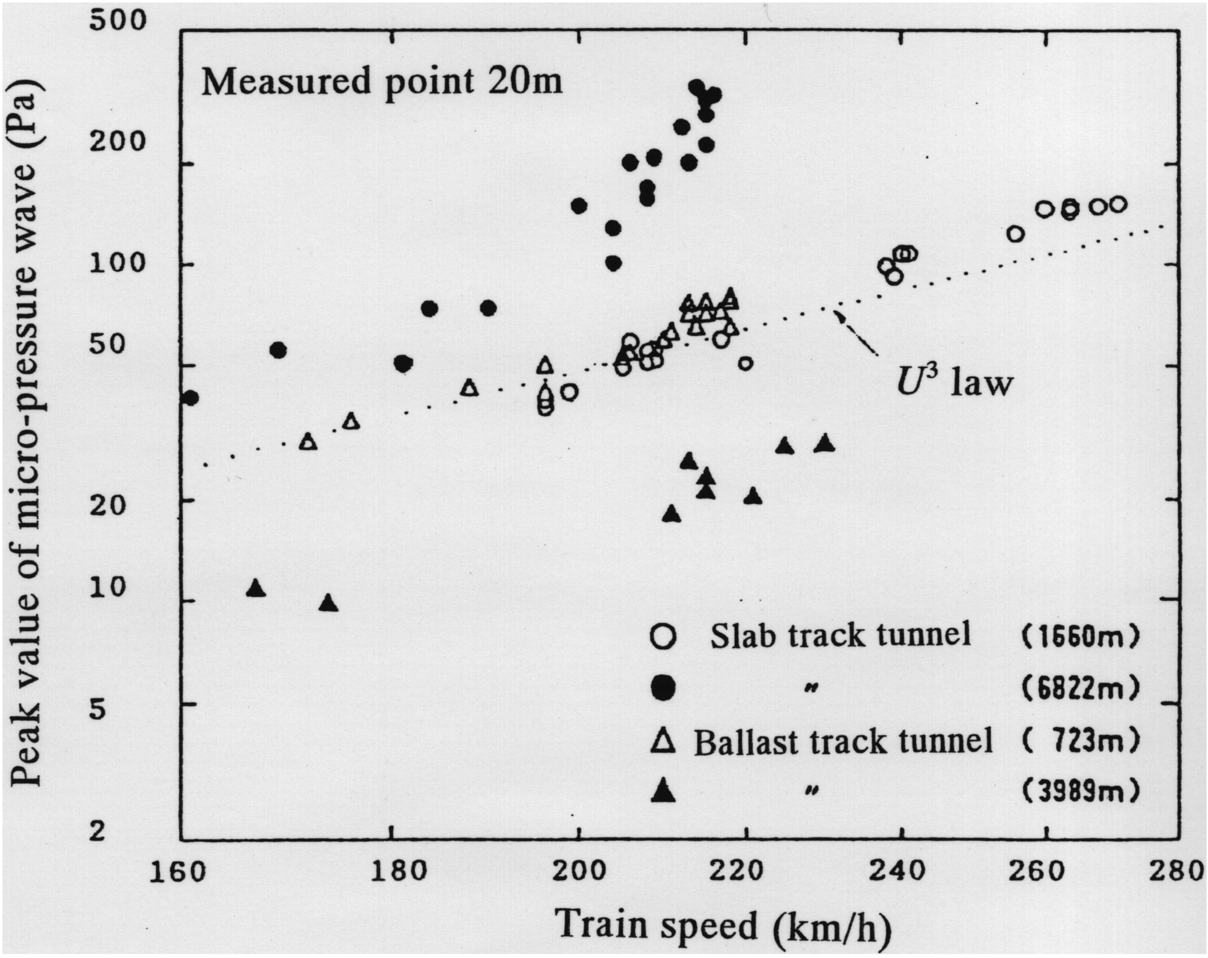

Figure 5: Relation between peak values of micro-pressure waves and train speed.

Figure 6: Tunnel hood (49 m long).

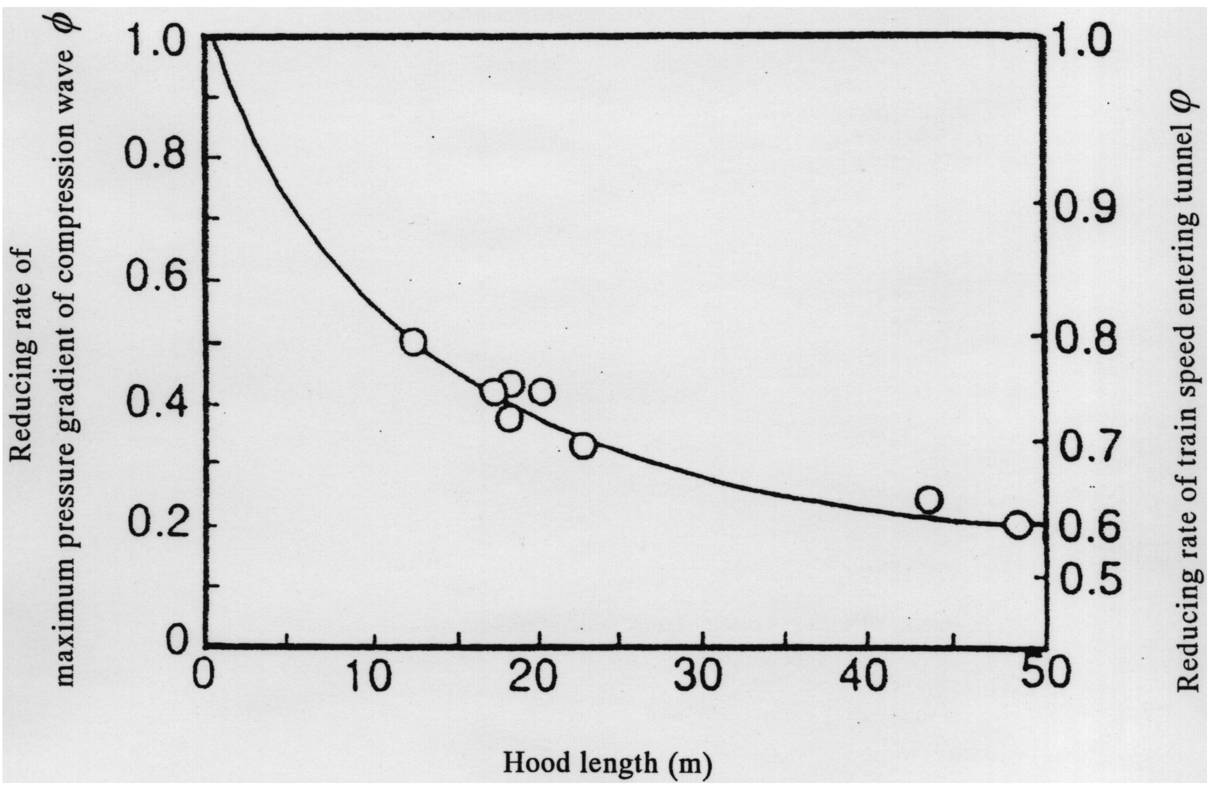

Figure 7: Relation between effect of tunnel hood and hood length.

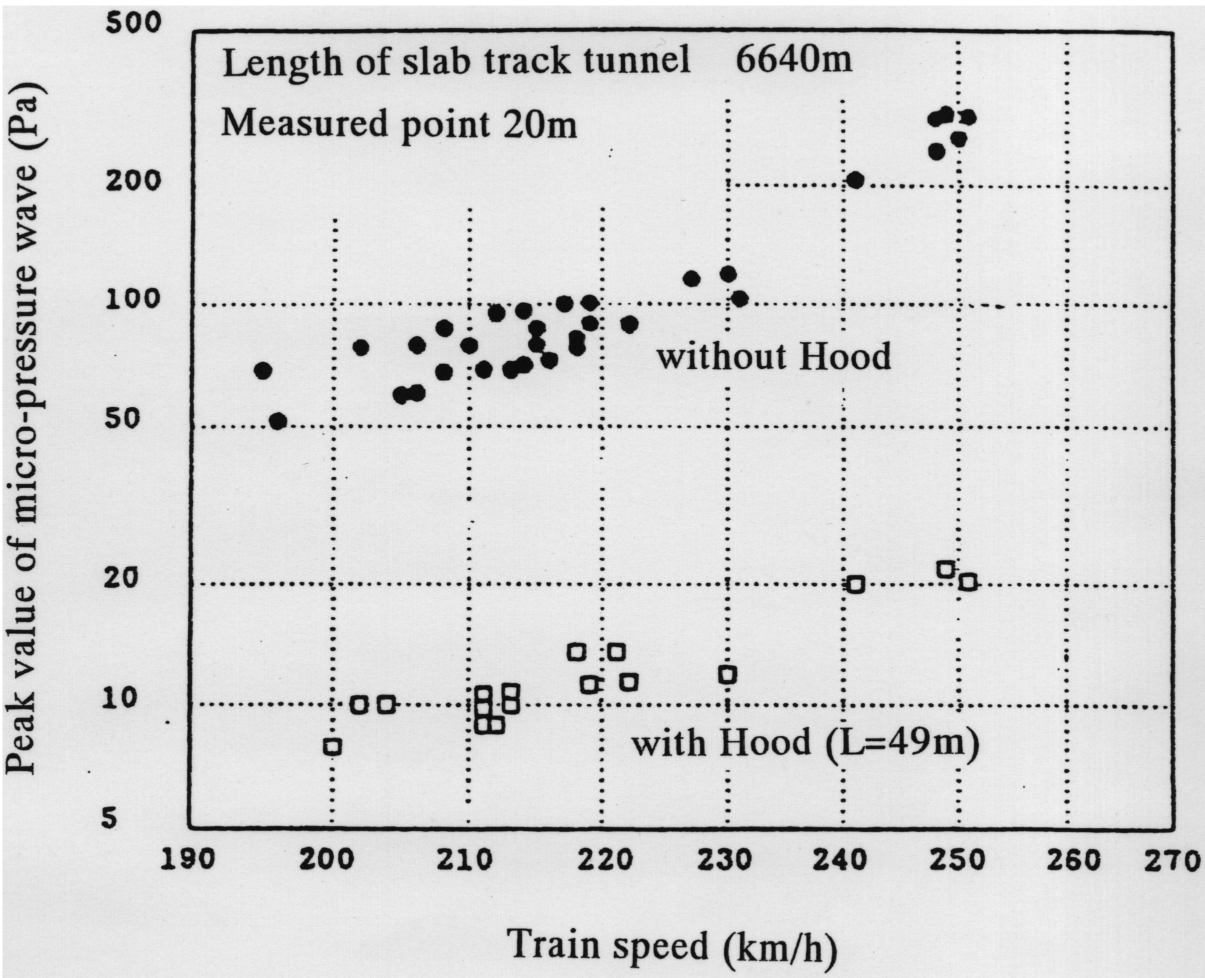

Figure 8: Effect of 49 m long tunnel hood.

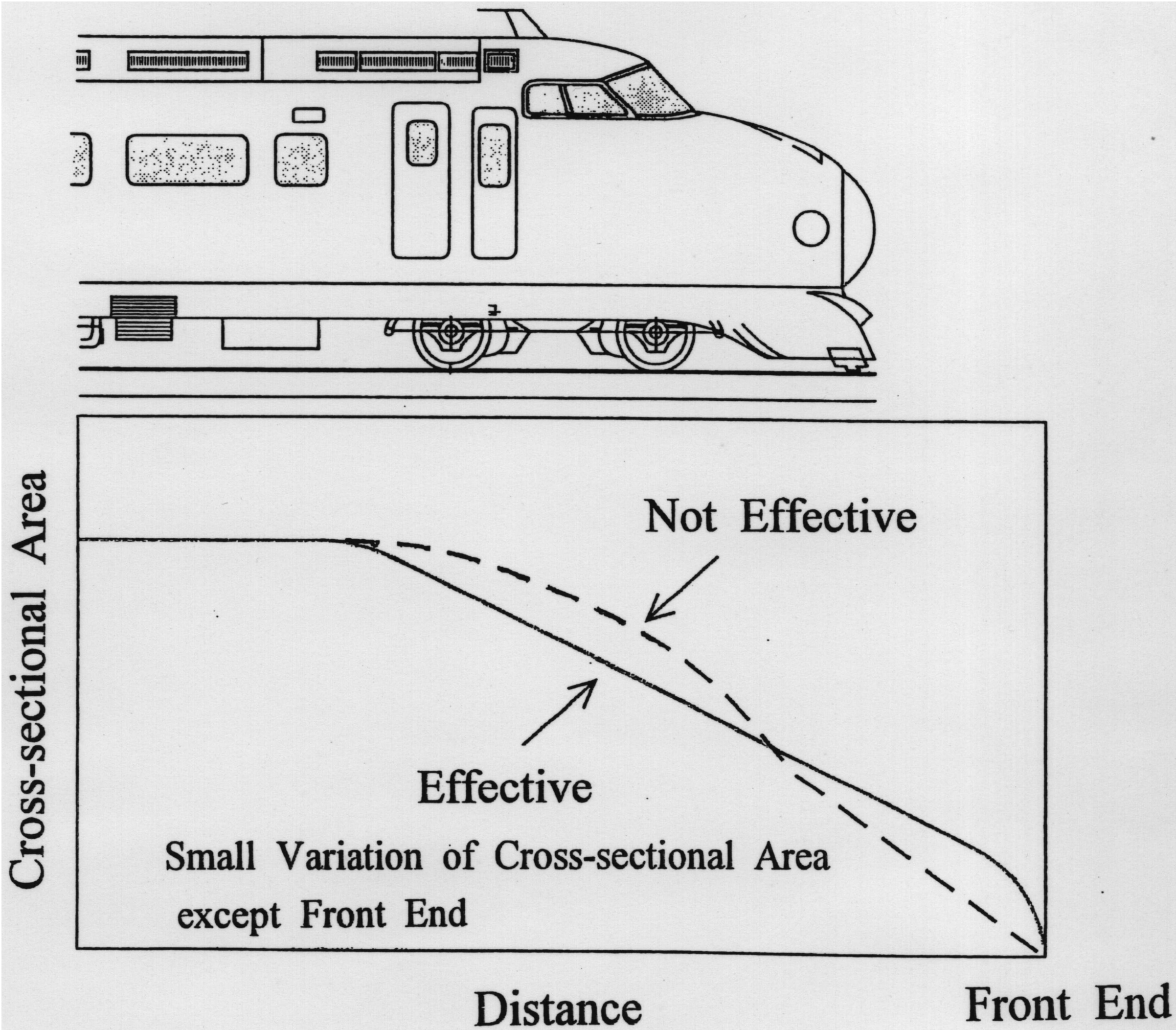

Figure 9: Variation of cross-sectional area of optimum nose.

Figure 10: Optimum nose shape of series 500 Shinkansen train (JR West).