Experimental Investigation of the Effects of Topography Around the Tunnel Portal on Micro-pressure Waves

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When a high speed train enters a tunnel, a micro-pressure wave radiates out from its exit portal. The micro-pressure wave can cause wayside environmental problems. Topography around the tunnel exit portal affects the peak value of the micro-pressure wave. In this paper, model experiments using a train model launcher were performed for investigating the effects of topography around the tunnel portal on the micro-pressure wave. Four types of topographic models, infinite flat ground, excavation on one side, excavation on both sides and elevated bridge, were used to measure the spatial distribution of the peak values of the micro-pressure waves. Furthermore, a modification of a prediction model for the peak value of the micro-pressure wave radiation was made on the basis of the experimental results.

Keywords: high-speed railway, micro-pressure wave, emission, topography

1. Introduction

A train entering a tunnel generates a compression wave in the tunnel. When the compression wave arrives at the tunnel exit portal after its propagation thorough the tunnel, the micro-pressure wave (MPW) radiates outward from the portal [1][2]. MPW can cause problems such as explosive noise and structural vibration. Therefore, it is important to develop methods to predict and reduce the peak value of MPW.

Yamamoto [1] showed that the main source of MPW is an outgoing flow from the tunnel exit portal excited by the compression wave, and that the strength of the source is almost proportional to the pressure gradient (\(\frac{\partial p}{\partial t}\)) of the compression wave arriving at the tunnel exit portal. For short tunnels, the peak value of MPW is proportional to \(U^3\) because the maximum value of pressure gradient (\((\frac{\partial p}{\partial t})_{\text{max}}\)) is approximately proportional to \(U^3\), where \(U\) is the train speed. For long slab track tunnels, the maximum value of MPW can be proportional to \(U^3\) to \(U^{10}\) because \((\frac{\partial p}{\partial t})_{\text{max}}\) of the compression wave increases as it propagates. As a result, the peak value of MPW heavily depends on the train speed. Countermeasures have become more urgent in recent years along with the increase in Japanese high-speed train speed, thereby calling for more accurate MPW prediction.

Yamamoto [1] formulated the effect of the topography around the tunnel portal on MPW using an opening angle from the exit portal (the solid angle). The formula is called the solid angle model in this paper. The solid angle model is a one dimensional model based on the assumption that the peak value distribution of MPW is spherically symmetric and commonly employed because of its simplicity. For real Shinkansen tunnels, however, the peak value of MPW depends on the observation positions even if they are spherically symmetric, because the distribution is three dimensional. Therefore, we need to make the effect of the topography around the tunnel portal clearer and more accurate.

Here, model experiments were performed to investigate the effect of the topography around the tunnel portal on MPW. Then, simple modification to the solid angle model was given based on the experimental results.

2. Model experiments

2.1 Experimental method

Model experiments were performed to clarify the effect of the topography around the tunnel portal on MPW. A train launcher facility was used as a compression wave generator [3]. MPWs were measured around the branch exit portal to avoid interference between the train model and the microphones [4].

Schematic drawings of the experimental apparatus are shown in Fig. 1 and Fig. 2. The model tunnel consists of a main tunnel and a branch, circular cylindrical pipe made of vinyl chloride, with inner diameter of 0.1 m. Each portal has no hood [2]. The nose shape of the train model is a revolution of ellipsoid and its diameter and length are 44.7 mm and 67.1 mm respectively. The train model was launched with the speed of 230 - 270 km/h. The distance between the main tunnel entrance and the junction between the main tunnel and the branch is around 8m. The branch pipe has a partition plate of 3 mm thickness for its...
entire length. The partition plate and the inner side of the branch pipe are glued. An assumption is made of the cross-sectional area of the upper semicircle of the branch exit portal, from which the cross-sectional area of the partition plate is excluded, as the tunnel exit portal; the experiment reported here is 1/130 of full scale considering that the cross-sectional area of the Japanese Shinkansen tunnel is $63.4 \text{ m}^2$.

Four types of topographic models, infinite flat ground, excavation on one side, excavation on both sides and elevated bridge, were used. Figure 3 and Table 1 show the topographic models and their specifications, respectively. The sizes of the topographic models are $1800 \text{ mm} \times 2000 \text{ mm}$ and are large enough for the effects of scattering waves from the boundary on MPW to be negligible.

MPWs are measured by microphones, Rion, NL-32, F-weighted, at the points 157 mm (20.4 m points) and 394 mm (51.2 m points) away from the center of the exit portal (observation distance). They are referred to hereafter as the 20 m points and 50 m points respectively. The microphone configuration for the excavation on one side is shown in Fig. 4 by way of example, where $h$ denotes the height of excavation. Pressure waveforms of the compres-
tion waves are measured by a wall mounted pressure transducer, Kulite, XCS-190-5-G, at the point 1 m apart from the exit portal.

When the lower semicircle of the branch portal was below the ground plate, the lower portal was made to be open. When it was exposed above the ground plate, the lower portal was made to be closed using a thin plate to avoid MPW emission from there.

2.2 Experimental resultse

Transfer functions between a compression waveform (input) and MPW (output) were obtained from the experimental results. MPW was calculated using the transfer function in the case where a reference waveform was input [4]. The reference waveform was given as \( p = 1 + \tanh(10 \cdot t) \) (kPa) and the speed of sound was given as 340 m/s. Figure 5 shows waveforms of MPWs calculated using the transfer functions for the excavation on both sides, \( r = 20 \), and \( \theta = 0^\circ \), where \( r \) is the magnitude of the observation vector from the center of the portal (distance from the center of the portal to the observation point), \( \theta \) is azimuth angle between the rail and the observation vector. Herein, the MPW calculated based on the experimental results were regarded to be the experimental results.

Figures 6 - 9 show the experimental results. In these figures, A and B denote measuring points 'on the ground' and 'on the hill or on the bridge', respectively, and the peak value of MPW denotes the mean value of the calculated maximum values of MPW using the transfer functions based on the experimental results [4]. These figures show that the space distribution of the peak values of MPW varies and becomes three dimensional as the topography varies. In front of the portal, the peak value of MPW has the maximum value for each case except 50 m points of the elevated bridge.

3. Effective solid angle

Predicting MPW emission requires mathematical models of (a) the source of MPW and (b) the scattering effect...
Fig. 9  Distribution of the maximum value of MPW, elevated bridge

of the topography. Yamamoto showed the following solid angle model considering both of them [1][2].

\[
p_{sw} = \frac{2S}{2\pi r^2} \frac{\partial p}{\partial \theta} \left( \frac{r - \ell}{c} \right) \tag{1}\]

Here, \( t \): time, \( p_{sw} \): the sound pressure of MPW, \( p \): the sound pressure of the compression wave, \( c \): the speed of sound in atmosphere, \( r \): the observation distance, \( \Omega \): the solid angle and \( S \): cross-sectional area of the exit portal.

Figure 10 shows a sphere with the radius of the observation distance \( r \) located at the center of the portal. Calculating the solid angle based on the definition in [5] using the exposed surface of the sphere in Fig. 10, which is expressed in blue color in the figure, the solid angle for the excavation on one side as the function of the observation distance \( r \) is given as follows:

\[
\Omega = \pi \left( 1 + \frac{w}{2} \right) \quad \text{for} \quad \frac{w}{2} < r < \sqrt{h^2 + \left( \frac{w}{2} \right)^2}, \tag{2}
\]

\[
\Omega = 2\pi \left( 1 - \frac{h}{r} \right) + \int_{\frac{w}{2}}^{r} \left( 2 \sin^{-1} \left( \frac{w}{2\sqrt{r^2 - z^2}} \right) \right) \left( \frac{z}{r} \right) \, dz, \tag{3}
\]

for \( r > \sqrt{h^2 + \left( \frac{w}{2} \right)^2} \),

where \( z \) is an integral value and \( w \) is a half distance from the center of the portal to the side wall. For Fig. 10, \( w \) is equal to the outer diameter of the tunnel. Figure 11 shows a comparison between the experimental results and the prediction results using (1) - (3). For this example, the prediction error for the peak values of MPW at \( \theta = 0^\circ \) and \( \theta = -90^\circ \) is not negligible.

In front of the portal, directivity of the MPW source cannot be ignored. The prediction model using a point dipole source to consider the directivity for infinite flat ground is expressed as

\[
p_{sw} = \left( 1 + \frac{\ell}{r} \cos \theta \right) \frac{2S}{2\pi c r} \frac{\partial p}{\partial \theta} \left( \frac{r - \ell}{c} \right) \tag{4}\]

with low frequency approximation, where \( \ell \) is the end correction. The factor \( \left( \ell/r \right) \cos \theta \) in (4) expresses the dipole correction. The calculation results are shown using (4) in Fig. 6 for comparison with the experimental results. We can see from the figure that they agree well.

We define \( \Phi \) as the effective solid angle as follows in order to correct the solid angle with more accuracy for other topography based on (4).

\[
\Phi = \left( 1 + \frac{\ell}{r} \cos \theta \right) \frac{2S}{p_{sw} \cos \theta} \frac{\partial p}{\partial \theta} \left( \frac{r - \ell}{c} \right) \tag{5}\]

And then, we use the correction factor defined as \( k = \Phi / 2\pi \). The correction factor denotes the ratio of the effective solid angle for a topography case to that for infinite flat ground which is equal to \( 2\pi \) (obtained by substituting \( h = 0 \) into (3)). Using \( \Phi \) or \( k \), we have

\[
[p_{sw}]_{\text{max}} = \left( 1 + \frac{\ell}{r} \cos \theta \right) \frac{2S}{\Phi c r} \frac{\partial p}{\partial \theta} \left( \frac{r - \ell}{c} \right)_{\text{max}} \tag{6}\]
\[= \left(1 + \frac{k}{r} \cos \theta \right) \frac{2S}{2\pi kr} \left[ \frac{\partial p}{\partial t} \right]_{\text{max}}. \tag{7} \]

We show \(k\) for each topography case based on (7) applied to the experimental results in Tables 2 - 7. In these tables, \(k = 1\) and \(k > 1\) respectively denotes that the peak value of MPW is equal to and smaller than that for infinite flat ground. In the cases of excavation on one side or excavation on both sides, \(k\) is larger than 1 or is almost equal to 1 at the larger azimuth angle observation points (\(|\theta| > 90\)) on the hill (B). For the elevated bridge case, \(k\) is greater than 1 at every observation point in this experiment.

Table 2 The correction factor \(k\) of the effective solid angle for excavation on one side 20 m points

| Azimuth angle \(\theta\) (°) | Height of excavation (m) | Observation point |
|-----------------------------|-------------------------|------------------|
| -135                        | 0.65 13 26              |
| -90                         | 0.9 0.7 0.6             |
| -45                         | 0.9 0.7 0.6             |
| 0                           | 0.9 0.7 0.6             |
| 45                          | 0.9 0.7 0.6             |
| 90                          | 0.9 0.7 0.6             |
| 135                         | 0.9 0.7 0.6             |

Table 3 The correction factor \(k\) of the effective solid angle for excavation on one side 50 m points

| Azimuth angle \(\theta\) (°) | Height of excavation (m) | Observation point |
|-----------------------------|-------------------------|------------------|
| -135                        | 0.65 13 26              |
| -90                         | 0.9 0.7 0.6             |
| -45                         | 0.9 0.7 0.6             |
| 0                           | 0.9 0.7 0.6             |
| 45                          | 0.9 0.7 0.6             |
| 90                          | 0.9 0.7 0.6             |
| 135                         | 0.9 0.7 0.6             |

Table 4 The correction factor \(k\) of the effective solid angle for excavation on both sides 20 m points

| Azimuth angle \(\theta\) (°) | Height of excavation (m) | Observation point |
|-----------------------------|-------------------------|------------------|
| 0                           | 0.65 0.3 0.2            |
| 45                          | 0.9 0.7 0.6             |
| 90                          | 0.9 0.7 0.6             |
| 135                         | 0.9 0.7 0.6             |

Table 5 The correction factor \(k\) of the effective solid angle for excavation on both sides 50 m points

| Azimuth angle \(\theta\) (°) | Height of excavation (m) | Observation point |
|-----------------------------|-------------------------|------------------|
| 0                           | 0.8 0.4 0.2             |
| 45                          | 0.9 0.8 0.6             |
| 90                          | 1.0 1.0 0.9             |
| 135                         | 1.1 1.1 1.1             |

Table 6 The correction factor \(k\) of the effective solid angle for elevated bridge 20 m points

| Azimuth angle \(\theta\) (°) | Distance from the ground (m) |
|-----------------------------|-----------------------------|
| 0                           | 10.2                        |
| 45                          | 1.0                         |
| 90                          | 1.0                         |
| 135                         | 1.2                         |

Table 7 The correction factor \(k\) of the effective solid angle for elevated bridge 50 m points

| Azimuth angle \(\theta\) (°) | Distance from the ground (m) |
|-----------------------------|-----------------------------|
| 0                           | 1.0                         |
| 45                          | 1.0                         |
| 90                          | 1.1                         |
| 135                         | 1.2                         |

4. Discussion

In this study, experiments were performed using the topographic models simulating the neighborhoods of the high-speed railway tunnel portals to investigate the spatial distribution of the peak values of MPW.

Tables 2 - 7 show that the effective solid angles \(\Phi\) and the correction factors \(k\) satisfy respectively \(3.8 < \Phi < 9.4\) and \(0.6 < k < 1.5\) for the experimental results except those in front of the portal. Maeda \(^{(6)}\) reported the field test results in which the effective solid angles are relatively small and \(2 < \Phi < 4\). In this study, at the observation points on the ground (A) in the case of excavation on both sides, a similar range of the effective solid angle to the Maeda’s results was obtained, namely, \(1.3 < \Phi < 4\).

Figures 7 and 8 show that, in the cases of excavation on one side and the excavation on both sides, the peak values of MPW at the observation points on the ground (A) become greater as their height \(h\) increase, and on the other hand, the peak values of MPW at the observation points on the excavation (on the hill, B) become as large as those...
for the infinite flat plate. Tables 2 - 7 present that, at the observation points on the excavation (on the hill, B), in the case of excavation on one side the effective solid angle or the correction factor varies a little according to change of \( h \) and \( r \), and in the case of excavation on both sides they almost keep the same constant values as those for infinite flat ground. The peak values of MPW at the 20 m point in the front of the portal in the cases of excavation on one side and the excavation on both sides of 13 m height are respectively 1.5 times and 3 times as large as those for infinite flat ground. In the case of excavation on both sides of 13 m height, at the 20 m point on the hill B, where there may be some residents, \( k \approx 1 \) and the peak values of MPW are almost the same as that for infinite flat ground plate, although at the observation point in front of the portal (on the ground, A), where no residents live, \( k \approx 0.3 \).

Figure. 9 shows that the peak values of MPW for the elevated bridge cases are smaller than those for infinite flat ground. In all results, \( k > 1 \) and the peak values of MPW become smaller as \( h \) become greater. Furthermore, from Fig. 9, for \( h = 0 \), the peak values of MPW with side walls become larger at \( \theta = 0^\circ \) and smaller at \( \theta = 90^\circ \) a little. It is possible to say that the effect of side walls are negligible although they slightly increase the directivity of MPW. On the other hand, at the observation points on the ground A, i.e. at the foot of the bridge, \( k > 1 \) for 20 m points and \( k \approx 1 \) for 50 m points, hence, a bridge girder affects the peak values of MPW functioning as sound barriers.

The solid angle model, which is in common use, is expressed as one of the one dimensional models based on the low frequency and far field approximation for the case where the effect of topography is relatively small. In this study, a modification of the solid angle model presented using one parameter expressing the effect of topography and tables of the parameter based on the experimental results were given. It is practical to use this model because of its simplicity and improvement of the prediction accuracy. When more accurate prediction is required, it is possible to calculate MPW using the Green function expressing the effect of topography [4], although the method requires much calculation time. It is necessary to expand the table based on additional experimental results or the numerical results using the Green function.

5. Conclusion

In this paper, model experiments were performed to clarify the effect of topography on micro-pressure waves (MPW) using topographic models simulating the neighborhood of the high-speed railway tunnel portals. The important knowledge obtained by this study is summarized as follows.

(1) The peak values of MPW on the ground for excavation on one side have larger values than those on infinite flat ground. The peak value of MPW at the 20 m point in front of the portal for excavation on one side of 13 m height case is 1.5 times as large as that for infinite flat ground. On the other hand, the peak values of MPW on the excavation (on the hill) have smaller values than those on infinite flat ground.

(2) The peak values of MPW on the ground for excavation on both sides have larger value than those on infinite flat ground. The peak value of MPW at the 20 m point in front of the portal for excavation on both sides of 13 m height case is 3 times as large as that for infinite flat ground. On the other hand, the peak values of MPW on the excavation (on the hill) are almost the same as those for infinite flat ground.

(3) The peak values of MPW on the ground or on the bridge for elevated bridges have smaller values than those on infinite flat ground. The effect of the bridge girder functioning as sound barrier cannot be considered to be negligible for the peak values of MPW at the 20 m point. The peak values of MPW at 50 m point for elevated bridge of less than 20 m distance from the ground are almost the same as those for infinite flat ground, and the effect of bridge is negligible.

(4) A modification of the prediction model for the peak values of MPW was carried out. Parameters for modification are shown in the tables on the basis of the experimental results.

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