

## TECHNICAL REPORT

**Improvement of energy-based calculation method for noise radiation from semi-underground road based on a field experiment**Shinichi Sakamoto<sup>1,\*</sup>, Toshio Matsumoto<sup>2</sup>, Sakae Yokoyama<sup>2</sup> and Osamu Funahashi<sup>3</sup><sup>1</sup>*Institute of Industrial Science, The University of Tokyo,  
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**Abstract:** To determine noise radiation characteristics from a semi-underground road structure and to confirm the validity of a calculation method for road traffic noise, we previously carried out an *in situ* experiment using loudspeakers at a semi-underground road with reflective surfaces under construction. Thereafter, we carried out another experiment at the same experimental site, focusing on the effect of the pavement of an absorptive road surface and of setting absorptive louvers on the aperture part. In this report, experimental results on the effect of the pavement of an absorptive road surface are described. On the basis of the experimental results, the accuracy of a practical calculation method for noise around a semi-underground road, the hypothetical point source method, specified in the ASJ RTN-Model 2008, was discussed. Through the discussion, the practical calculation method was partially revised. That is, the effect of the absorption of the road surface was included in a correction term describing the sound power level of a hypothetical sound source that takes into consideration the multiple reflections between the ceiling and the road surface.

**Keywords:** Road traffic noise, ASJ RTN-Model, Semi-underground road, Field experiment

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## 1. INTRODUCTION

Noise propagation around a semi-underground road is complicated owing to multiple reflections and diffraction inside the road structures. In the practical prediction of road traffic noise, the ASJ RTN-Model published by the Acoustical Society of Japan, a hypothetical point source method was first proposed in the Model 2003 [1], and the parameters that were necessary to set according to the dimensions of the road structure and the equation that determined the sound power level of the hypothetical source were updated in the Model 2008 [2]. The calculation method was constructed on the basis of the results of scale model experiments [3] and a wave-based numerical analysis [4]. Thereafter, in 2004, we carried out a field experiment at a real semi-underground road under construction using a loudspeaker as the sound source to validate the hypothetical point source method and the applicability of two-dimensional wave based numerical

analysis [5,6]. The surface of the semi-underground road was bare concrete when the first experiment was performed, and therefore the validation of the calculation method was limited to a reflective case. In 2010, we were able to validate the applicability of the calculation method to a road where noise measures had been introduced. In this report, experimental results on noise propagation for the two cases where the road surface was (1) reflective paved with stone matrix asphalt and (2) absorptive paved with drainage asphalt are described. On the basis of the experimental results, a calculation method for the sound power of a hypothetical source when the road structure is absorptive is investigated.

## 2. FIELD EXPERIMENT

Figure 1 shows the measurement site. An experimental area of 200 m length was selected on a straight part of the semi-underground road. On the road surface of the underground structure, discrete sound source points were arranged as shown in Fig. 2, and a measurement cross section was centered on the experimental area. On the

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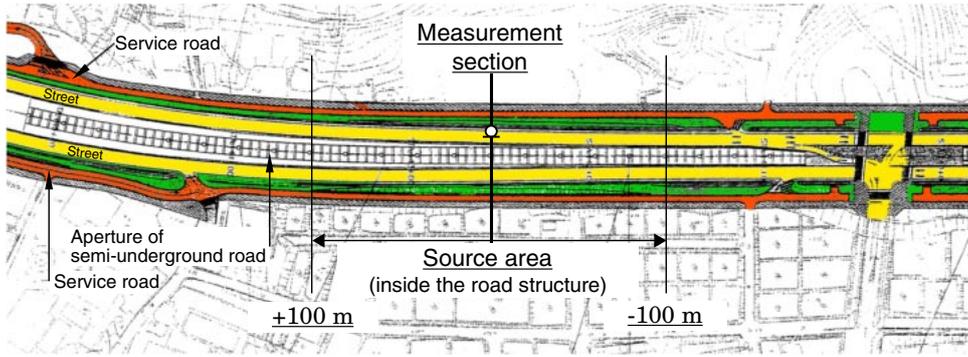


Fig. 1 Measurement site.

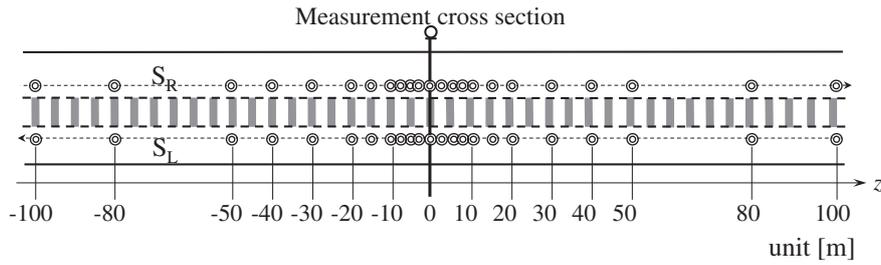


Fig. 2 Sound source positions.

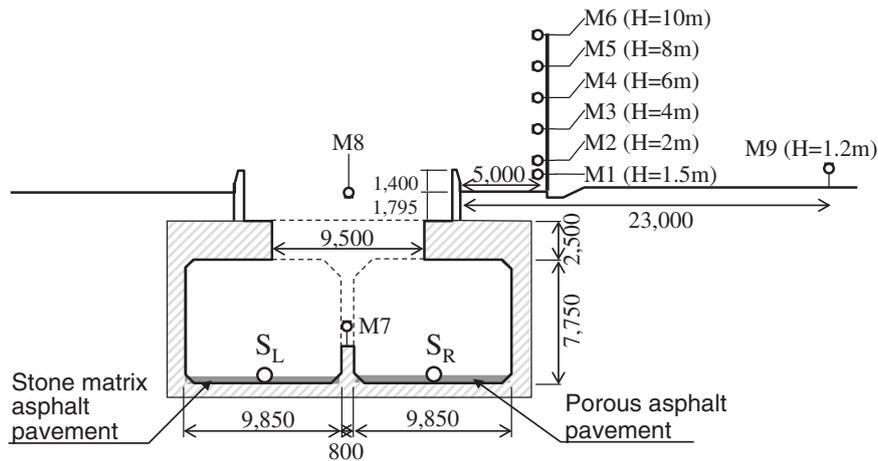


Fig. 3 Sectional shape of semi-underground road under investigation.

measurement cross section, nine microphones were set as shown in Fig. 3. Measurement points M1 to M6 sensed the vertical distribution of the sound radiating from the aperture to the surrounding space, at M7 and M8, the energies of the sound inside the road structure and radiating through the aperture were measured, and at M9, the sound pressure level at the roadside was measured. In this investigation, the sound pressure levels measured at M1 to M6 were examined for discussion of the sound radiation characteristics from the aperture. When this experiment was performed, only the  $S_R$  side in Fig. 3 was paved with absorbent porous asphalt, and the  $S_L$  side was acoustically reflective (stone matrix asphalt pavement). At measurement

points M1 to M6, six omnidirectional microphones were set on an extendable pole of 10 m height on the  $S_R$  side. Under the configuration described above, sound propagation characteristics from source points set inside the road structure to measurement points set at the measurement section were measured using an omnidirectional loudspeaker.

### 2.1. Sound Propagation Measurement

#### (1) Field measurement

The heptahedron loudspeaker simulating an omnidirectional source shown in Fig. 4 was discretely set at each source point on both driving lanes, as shown in Fig. 2, and the sound propagation characteristics from the sources to

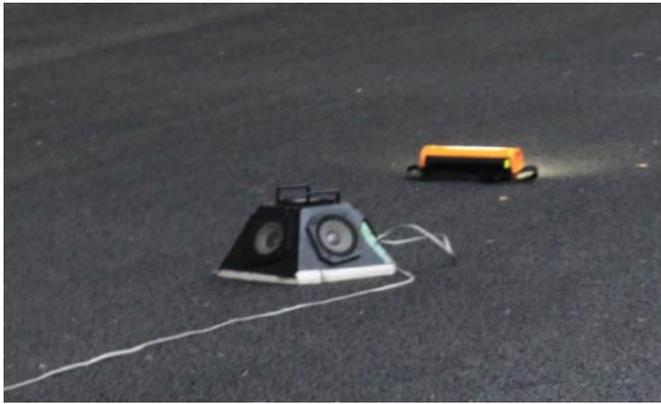


Fig. 4 Heptahedron loudspeaker used in the experiment.

the microphones were determined by impulse response measurements using swept sine signals. Outdoor sound propagation measurement is usually affected by disturbances such as extraneous noise and the fluctuation of meteorological conditions. In particular, in the case of measurement in a suburban area, the influence of extraneous noise is serious, and it is necessary to ensure a sufficient signal-to-noise (S/N) ratio. In this experiment, swept sine signals with a long duration were applied to obtain a sufficient S/N ratio for long-distance propagation measurements [6], and signals with the durations listed in Table 1 were applied considering the level of the background noise around the measurement site. The measured impulse responses were filtered by a 1/1 octave band in the frequency range from 125 Hz to 4 kHz center frequencies, and the obtained band-limited impulse responses were integrated in the time domain to obtain the sound pressure exposure level.

(2) Sound energy level measurement and correction of sound pressure exposure levels

The sound energy level of the loudspeakers to which these swept sine signals was applied was measured by the

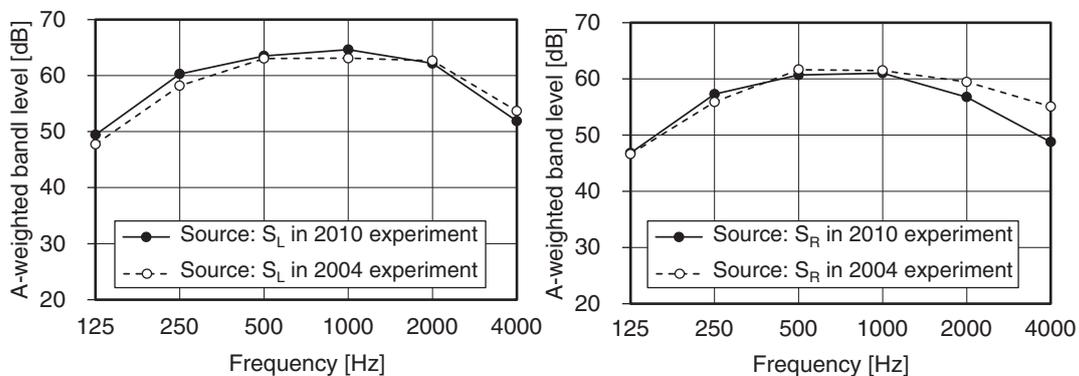
Table 1 Durations of swept sine signals.

Source position	Duration of signal
-100 m, -80 m	60 s/octave band
-50 m to 50 m	Pink TSP for 30 s (125 Hz to 4 kHz)
80 m	60 s/octave band
100 m	180 s/octave band

reverberation room method in advance of the field experiment. Based on the measured sound energy levels, correction values to simulate road traffic noise having A-weighted spectral characteristics under a steady-state running condition on a dense asphalt pavement road as specified in ASJ RTN-Model 2008 with an overall sound energy level of 100 dB were obtained as  $\Delta L_{A,RTN}(f)$ . Sound pressure exposure levels measured in the field experiment were corrected by using  $\Delta L_{A,RTN}(f)$  for each frequency, and finally, the obtained sound pressure exposure levels in all frequency bands were summed in energy-based to obtain the A-weighted sound pressure exposure levels at the measurement points. In the same manner, the results of the experiment in 2004, which are used for reference in the following sections, were re-analyzed using the spectral characteristics specified in ASJ RTN-Model 2008.

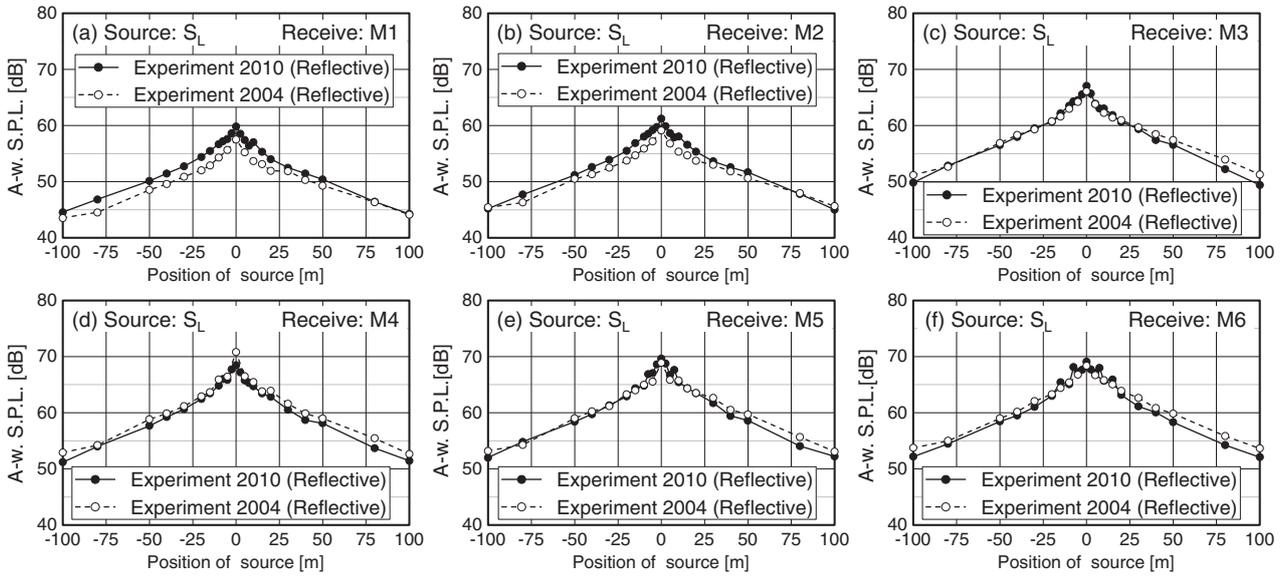
## 2.2. Comparison of Measurement Results between 2004 and 2010

Figures 5(a) and 5(b) show a comparison between the frequency characteristics of the measurement results at M6 for the experiments in 2004 and 2010 when the sound source was positioned at  $z = 0$  m. Whereas the A-weighted band levels when the source is on the lane  $S_L$  are similar, the levels for the source on lane  $S_R$  in 2010 are smaller than

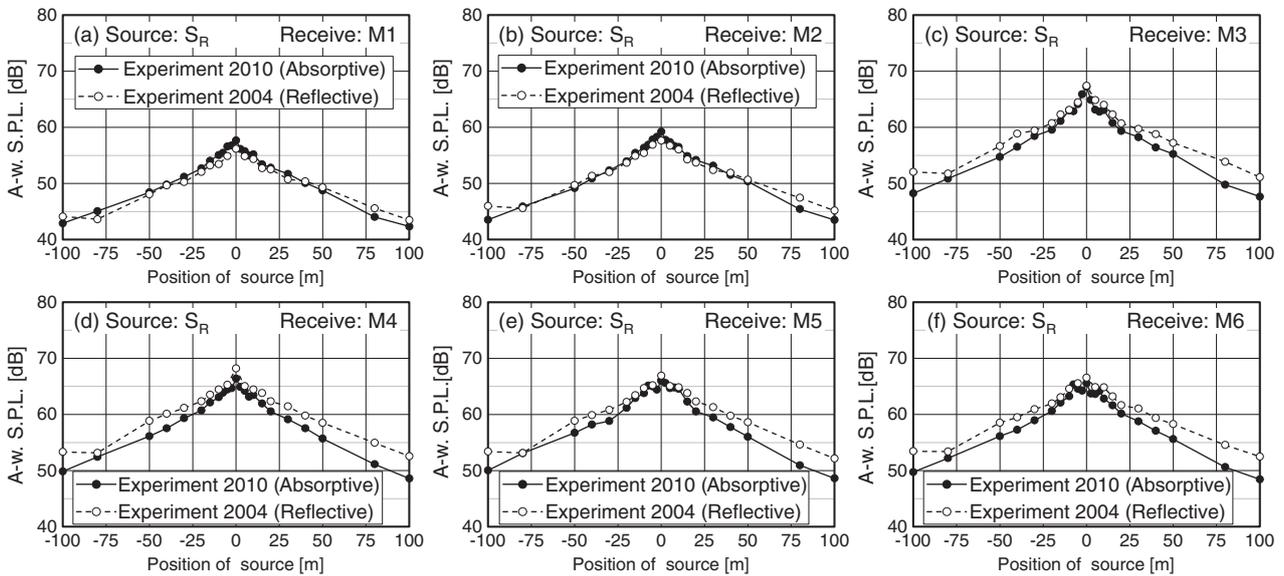


(a) Source at  $S_L$ , 2004 : reflective 2010: reflective. (b) Source at  $S_R$ , 2004 : reflective 2010: absorptive.

Fig. 5 Comparison of A-weighted band level between experiments in 2004 and 2010.



**Fig. 6** Comparisons of unit patterns of A-weighted sound pressure level for sound source at on lane  $S_L$ .



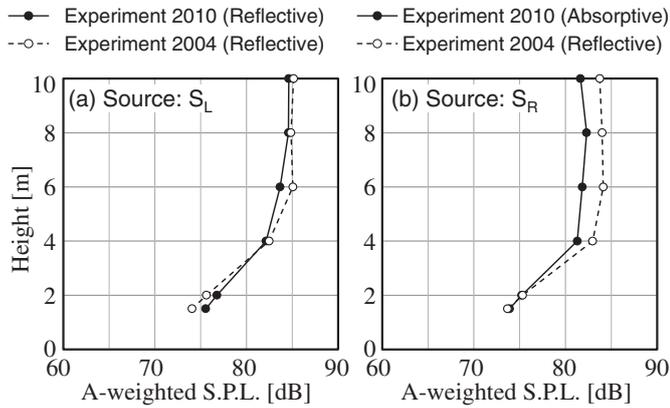
**Fig. 7** Comparisons of unit patterns for A-weighted sound pressure level for sound source at on lane  $S_R$ .

those in 2004 at high frequencies because the road surface was treated to improve its sound absorbance in 2010.

Figures 6(a) to 6(f) and Figs. 7(a) to 7(f) show unit patterns of the A-weighted sound pressure level at M1 to M6 when the sound source was moved along lanes  $S_R$  and  $S_L$ , respectively. In the case where the source is set on lane  $S_L$  (see Fig. 6), which has a reflective road surface, the sound attenuation characteristics obtained by changing the sound source position in the experiment in 2010 are similar to those for the experiment in 2004. Regarding the maximum value in the unit patterns, the measurement results in 2010 are slightly larger than those in 2004. On the other hand, in the case where the source is set on lane  $S_R$  (see Fig. 7) and the source is distant from the measurement

cross section, the sound pressure levels measured in 2010 becomes markedly smaller than those measured in 2004. Sound attenuation along the absorptive road surface causes the reduction of the sound pressure levels.

To simulate noise from road traffic flow, the sound pressure level for a line source on each lane was calculated by integrating the square of the sound pressure over the  $\pm 100$  m range of the experimental area assuming the line source condition with a sound energy level per unit length of 100 dB/m. The calculation results are shown in Figs. 8(a) and 8(b), where the sound pressure level is plotted as a function of height. When the source was located on lane  $S_L$ , which had a reflective surface, differences between the data in 2010 and the data in



**Fig. 8** Sound pressure level for a line source with 100 dB/m sound energy level.

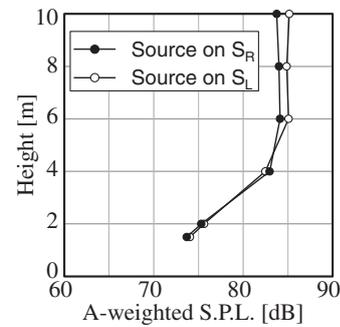
2004 are small, whereas differences of approximately 2 dB are observed at receiving points higher than 4 m when the source was located on lane S<sub>R</sub>, which had an absorptive surface.

### 3. VALIDATION OF ENERGY-BASED PREDICTION MODEL PROPOSED IN ASJ RTN-MODEL 2008

The practical calculation model specified in ASJ RTN-Model 2008, the hypothetical point source method, was applied to the semi-underground road structure under investigation to examine the validity of the prediction model. In the method, the sound pressure level is calculated for the sound propagation from a directional sound source and the directivities are specified for several typical geometrical conditions. The calculation method is described in detail in the literature [2]. According to the scope of the hypothetical point source method, its application is limited to cases where the traffic flows (combinations of vehicle classification and traffic volume) in lanes with traffic moving in opposite directions are almost equivalent, and therefore a case where a sound source exists on individual lanes is outside of the application range. However, the prediction method was applied to such a case in this experiment to determine the validity of the method, owing to the fact that the results of the vertical sound pressure distribution for the sound sources on individual lanes measured in the 2004 experiment were similar as shown in Fig. 9. The level differences between the two cases are within 1.0 dB except for M6, where the difference is 1.4 dB.

#### 3.1. Calculation Conditions

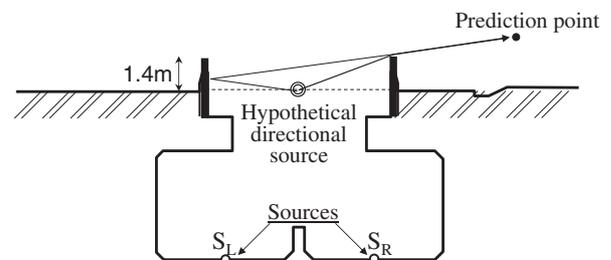
In ASJ RTN-Model 2008, the values of parameters regarding the directivity of the noise radiation from the aperture are listed for several cases [2]. Among them, the values listed in Table 2, which are determined for a case



**Fig. 9** Comparison of sound pressure level measured for sources on lanes S<sub>R</sub> and S<sub>L</sub>.

**Table 2** Values of parameters regarding directivity applied in this study.

$a$ [—]	$n_{\max}$ [—]	$\beta$ [—]	$\Delta L_{\text{dir,su}}$ [dB]
0.13	1.2	2	1.4



**Fig. 10** Arrangement of the hypothetical directional source.

having a road structure width ( $L$ ) 20 m, aperture width ( $W$ ) 10 m, underground part height ( $H$ ) 5 m and overhangs thickness ( $T$ ) 4 m, were used for the calculation. In the hypothetical point source method, a correction due to sound diffraction by a barrier is considered if a noise barrier is installed in the vicinity of the aperture. On the measurement site, barriers of 1.4 m height are installed on both sides in the vicinity of the aperture, as shown in Fig. 10, and multiple reflections and diffraction occur between the barriers. In this study, the contributions from the first and second reflections between the barriers were considered.

#### 3.2. Comparison between Experiment and Calculation

Figures 11(a) to 11(f) and 12(a) to 12(f) show comparisons between the experimental results and the calculation results. Here, (a) to (e) show A-weighted sound pressure levels for different point sources, and (f) shows the A-weighted sound pressure level for a line source obtained by the procedure described in Sect. 2.1. When the source is on the absorptive road surface (see Fig. 12), good agree-

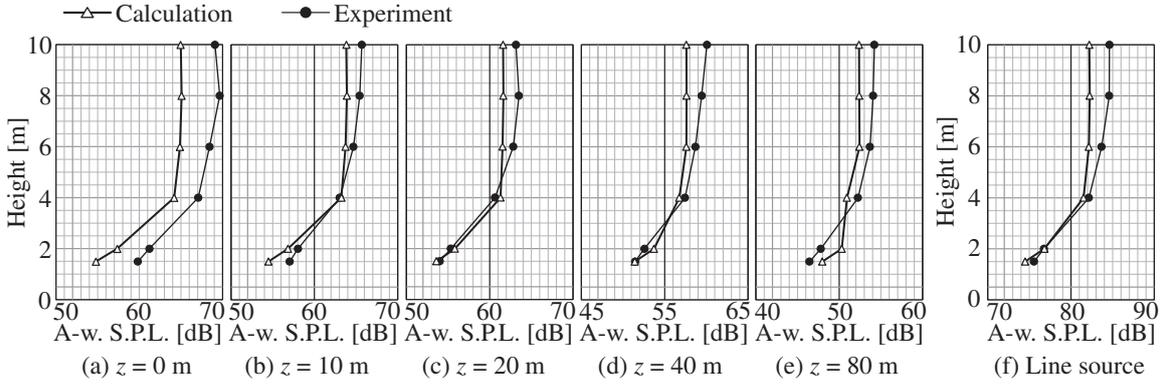


Fig. 11 Comparison between calculation by ASJ RTN-Model 2008 and experiment for the source at on lane  $S_L$ .

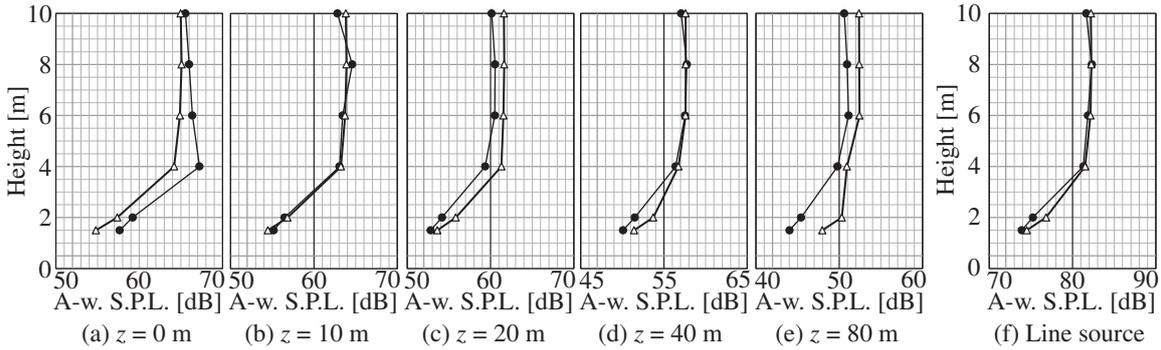


Fig. 12 Comparison between calculation by ASJ RTN-Model 2008 and experiment for the source at on lane  $S_R$ .

ment between the calculation and experiment is generally observed. Regarding the sound pressure level for the line source, the differences between the calculated and experimental values are small. On the other hand, when the source is on the reflective road surface (see Fig. 11), the calculated results tend to be lower than the experimental ones. In particular at  $z = 0$  m, the calculated results are 3 to 5 dB lower than the experimental results. Regarding the sound pressure level for the line source, the difference exceeds 2 dB at the high positions of M5 and M6. As shown by these results, the sound pressure level around a semi-underground road structure can differ to some extent by varying the absorbing condition of the road surface, and therefore such a difference due to the condition of the road surface should be reflected in the prediction model. Hence, in the next section, the description of the sound power level of the hypothetical point source in the hypothetical point source method is examined.

#### 4. REVISION OF DESCRIPTION OF SOUND POWER LEVEL OF HYPOTHETICAL POINT SOURCE

##### 4.1. Formulation

In ASJ RTN-Model 2008, the following description is given as the correction for the dimensions of a semi-

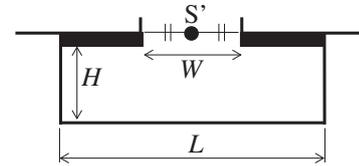


Fig. 13 Parameters for calculation of  $\Delta L_{dim,su}$ .

underground road structure to the apparent sound power level of the hypothetical directional source;

$$\Delta L_{dim,su} = 10 \log_{10} \left( \frac{2}{\pi} \tan^{-1} \frac{W}{2H} + \frac{\pi WH}{3L^2} \right), \quad (1)$$

where  $L$ ,  $W$ , and  $H$  are the width of the road [m], the width of the aperture [m], and the height of the semi-underground section [m], respectively, as shown in Fig. 13. The derivation of the correction is described in the literature [4]. The first term in Eq. (1) represents a sound energy directly arriving at the aperture, and the second term represents the sum of the contributions from an infinite series of mirror sources, as shown in Fig. 14, considering multiple reflections in the horizontal direction. Now let us suppose that a real sound source  $S$  has a sound energy  $E$ , then the sound energy directly arriving at the aperture and

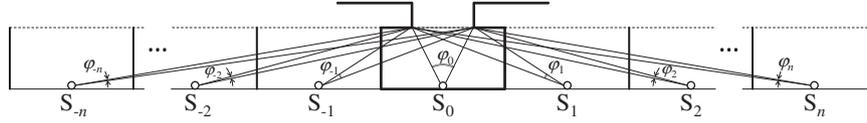
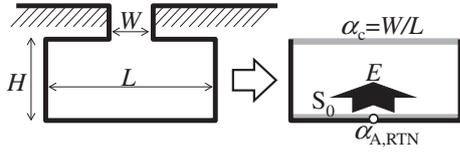
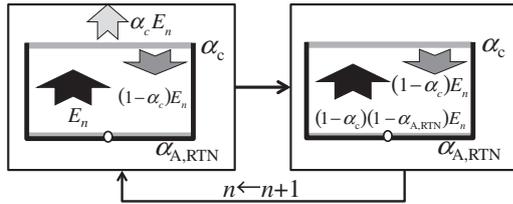


Fig. 14 Contributions from a series of mirror sources.



(a) Simplified model of semi-underground road structure.



(b) Multiple reflections between road surface and ceiling and energy consumption inside the structure.

Fig. 15 Modeling of sound field inside the semi-underground road structure.

after multiple reflections between the sidewalls,  $E_h$ , is expressed by

$$E_h = E \cdot \left( \frac{2}{\pi} \tan^{-1} \frac{W}{2H} + \frac{\pi WH}{3L^2} \right). \quad (2)$$

As is clear from Eq. (1), the correction term does not include the effect of sound absorption on the road surface. Now we consider multiple vertical reflections between the road surface and the ceiling to add a correction term to Eq. (1) for absorption on the road surface.

Figures 15(a) and 15(b) show a cross-sectional model of multiple reflections between a road surface and ceiling. As shown in Fig. 15(a), the ceiling of the road structure, consisting of an aperture of  $W$  [m] width and rigid a ceiling of  $L - W$  [m] width, is simply modeled as a homogeneous surface with an equivalent absorption coefficient of  $\alpha_c = W/L$ , and the road surface is assumed to have an absorption coefficient of  $\alpha_{A,RTN}$ . Then, the sound field inside the semi-underground road structure is modeled as having two parallel homogeneous flat boundaries with absorption coefficients of  $\alpha_c$  and  $\alpha_{A,RTN}$ . In such a simple sound field, multiple reflections in the vertical direction are considered. After a sound energy  $E$  radiated from a source propagates toward the ceiling, the ceiling absorbs part of the propagating energy,  $\alpha_c E$ . The absorbed energy  $\alpha_c E$  corresponds to the energy radiated to outside of the semi-underground road structure. The residual energy  $(1 - \alpha_c)E$

is reflected by the ceiling and propagates toward the road surface. The road surface absorbs part of the propagating energy  $\alpha_{A,RTN} (1 - \alpha_c)E$ , and the residual energy  $(1 - \alpha_{A,RTN})(1 - \alpha_c)E$  is reflected by the road surface. The energy  $(1 - \alpha_{A,RTN})(1 - \alpha_c)E$  propagates toward the ceiling. Upon repeated absorption and reflection of the sound energy inside the road structure gradually decreases. Assuming the sound energy existing inside the road structure after the  $n$ th reflection to be  $E_n$ , then the relationship between  $E_n$  and  $E_{n+1}$  is expressed as

$$E_{n+1} = E_n (1 - \alpha_c)(1 - \alpha_{A,RTN}). \quad (3)$$

Therefore,  $E_n$  is calculated as

$$E_n = E (1 - \alpha_c)^n (1 - \alpha_{A,RTN})^n. \quad (4)$$

On the other hand, at the  $n$ th reflection step, the sound energy  $\alpha_c E_n$  radiates from the ceiling to outside of the road structure. Therefore, the total sound energy radiated after multiple reflections,  $E_v$ , is calculated by summation of the amounts of radiated energy,

$$E_v = \alpha_c \sum_{n=1}^{\infty} E_n. \quad (5)$$

Considering that  $\alpha + \alpha^2 + \alpha^3 + \dots = \alpha/(1 - \alpha)$  and  $\alpha_c = W/L$ ,  $E_v$  is expressed

$$E_v = E \frac{(L - W)(1 - \alpha_{A,RTN})W}{\{L\alpha_{A,RTN} + (1 - \alpha_{A,RTN})W\}L}. \quad (6)$$

From Eqs. (2) and (6), the total energy radiated through the aperture of the semi-underground road is expressed as

$$\begin{aligned} E_{\text{Total}} &= E_h + E_v \\ &= E \cdot \left[ \frac{2}{\pi} \tan^{-1} \frac{W}{2H} + \frac{\pi WH}{3L^2} \right. \\ &\quad \left. + \frac{(L - W)(1 - \alpha_{A,RTN})W}{\{L\alpha_{A,RTN} + (1 - \alpha_{A,RTN})W\}L} \right]. \quad (7) \end{aligned}$$

Consequently, the correction term regarding the dimensions and absorption characteristics of the road surface is described as

$$\begin{aligned} \Delta L_{\text{dim,su}} &= 10 \log_{10} \left[ \frac{2}{\pi} \tan^{-1} \frac{W}{2H} + \frac{\pi WH}{3L^2} \right. \\ &\quad \left. + \frac{(L - W)(1 - \alpha_{A,RTN})W}{\{L\alpha_{A,RTN} + (1 - \alpha_{A,RTN})W\}L} \right]. \quad (8) \end{aligned}$$

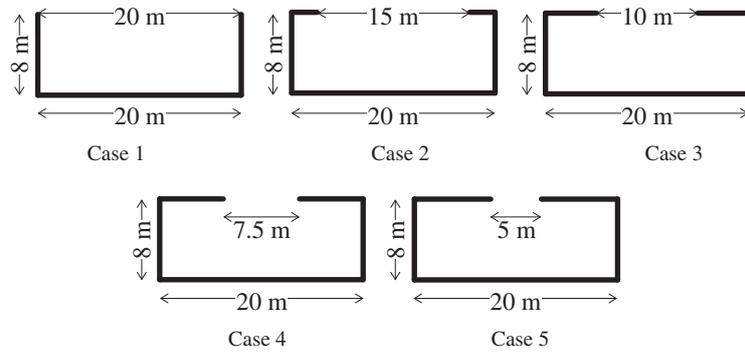


Fig. 16 Dimensions of five semi-underground road structures under investigation.

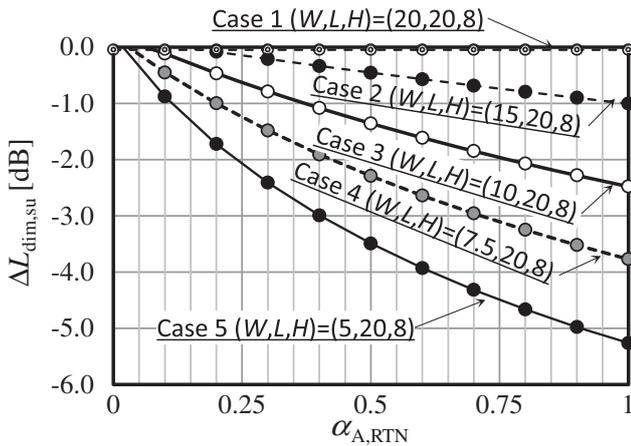


Fig. 17 Results of a parameter study on the absorption coefficient of the road surface.

4.2. Parameter Study

$\Delta L_{dim,su}$  formulated in Sect. 4.1 was calculated for the five cases shown in Fig. 16 and the influence of the absorption coefficient of the road surface was parametrically investigated. The results of the calculation are shown in Fig. 17. In case 1,  $\Delta L_{dim,su}$  is almost 0 dB regardless of the absorption coefficient of the road surface because

multiple reflections do not occur. In cases 2, 3, 4, and 5, the  $\Delta L_{dim,su}$  becomes increasingly negative as the absorption coefficient increases. Regarding differences among the cases, the variation in  $\Delta L_{dim,su}$  increases as the width of the aperture decreases.

4.3. Comparison between Experiment and Revised Calculation

Figures 18(a) to 18(f) and 19(a) to 19(f) show comparisons between experimental results and revised calculation results. In the calculation,  $\alpha_{A,RTN}$  was 0 for the reflective road surface and 1.0 for the absorptive road surface. For the absorptive road surface, the calculation results were the same as those obtained by the original calculation method including the correction term with Eq. (1) because the contribution newly introduced by Eq. (6) becomes zero upon substituting  $\alpha_{A,RTN} = 1.0$ , and therefore the graphs in Fig. 19 are the same as those in Fig. 12. For the sound source on lane  $S_L$ , the correction value regarding the dimensions and sound absorption obtained by Eq. (8) becomes 1.2 dB larger than the value of the correction obtained by Eq. (1). Consequently, the correspondence between the experiment and calculation was increased.

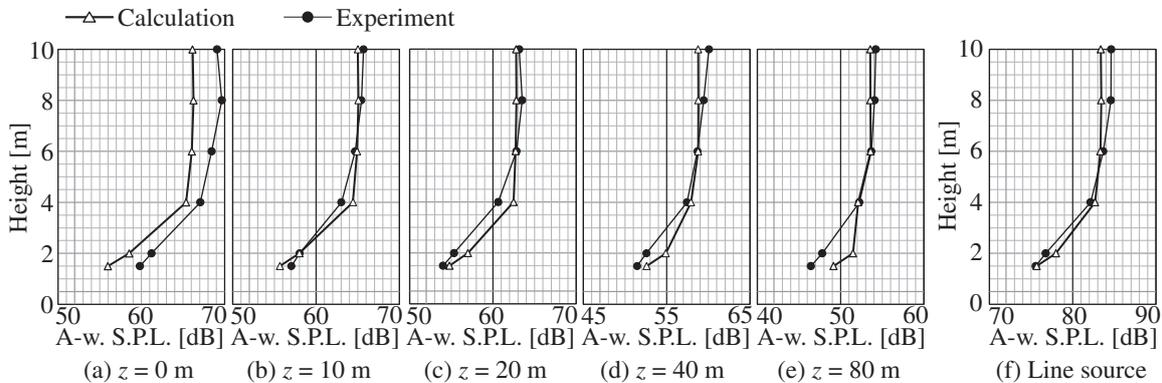
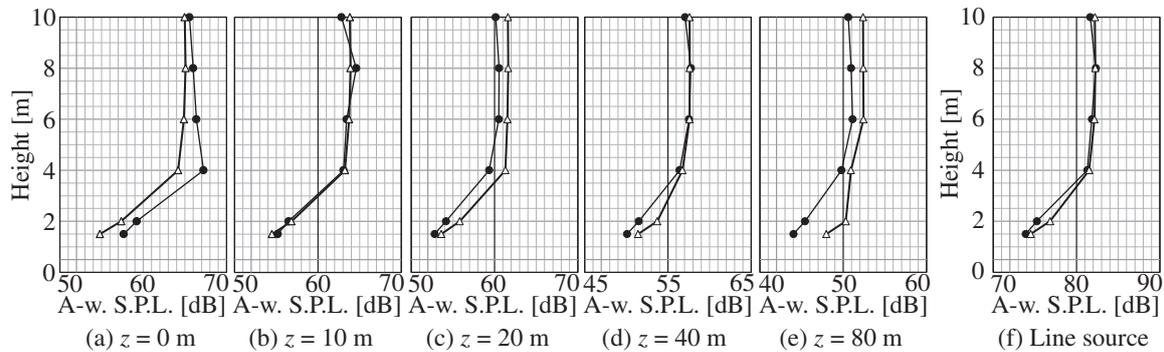


Fig. 18 Comparison between calculation by revised sound power model introduced in this study and experiment for the source at on lane  $S_L$ .



**Fig. 19** Comparison between calculation by revised sound power model introduced in this study and experiment for the source at on lane  $S_R$ .

## 5. CONCLUSION

A field experiment on sound propagation around a semi-underground road paved with a reflective surface on one lane and an absorptive surface on the other lane was conducted. Comparing the experimental results with those obtained by a previous experiment carried out in 2004, in which all the boundaries were reflective, the effect of sound absorption treatment on the road surface was investigated. The practical calculation model of road traffic noise around a semi-underground road, the hypothetical point source method did not previously include the effect of absorption on a road surface. Therefore, in this study, a correction term that included the absorption effect of a road surface was newly deduced. The validity of the deduced correction term was confirmed by comparing the results of a calculation using the deduced correction term with the experimental results.

## ACKNOWLEDGEMENT

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