

## TECHNICAL REPORT

**Simple calculation model for noise propagation  
in city street canyons based on a diffusion method**Yasuaki Okada<sup>1,\*</sup>, Koichi Yoshihisa<sup>1,†</sup> and Kazuhiro Kuno<sup>2,‡</sup><sup>1</sup>*Faculty of Science and Technology, Meijo University,  
Shiogamaguti 1-501, Tempaku-ku, 468-8502 Japan*<sup>2</sup>*Faculty of Engineering, Aichi Institute of Technology,  
Yachigusa 1247, Yakusa-cho, 470-0392 Japan**(Received 31 March 2009, Accepted for publication 20 July 2009)*

**Abstract:** In urban areas, medium and high-rise buildings are usually constructed on both sides of an arterial road and a viaduct road often exists above it. There are many reflections by building facades, the pavement and the underside of the viaduct road in such places. Therefore the roadside noise levels may exceed the recommended limits in city street canyons. In this paper, a simple calculation model for estimating the mean increase in noise level owing to multiple reflections has been proposed in order to predict road traffic noise in city street canyons more accurately. This model is based on a diffusion method. We have also investigated the effects of multiple reflections on noise propagation using a 1:40 scale model of a city street canyon with a viaduct road. As a result of this study, it has been found that the mean increase in noise level owing to multiple reflections by building facades and the underside of the viaduct road in built-up urban areas is up to about 8 dB. Comparisons between the results of experiments and calculations show that the simple calculation model gives results consistent with experimental ones.

**Keywords:** Road traffic noise, Street canyon, Multiple reflections, Building facade, Diffusion method

**PACS number:** 43.50.Lj, 43.28.Js [doi:10.1250/ast.31.95]

## 1. INTRODUCTION

The presence of medium and high-rise buildings on both sides of an urban road can cause an increase in the noise level owing to multiple reflections between building facades and the pavement. Thus, noise in urban areas is a problem of major importance for people living in modern large cities. In addition to buildings, a viaduct road is often constructed above the flat road. For such road structures, the prediction of road traffic noise is very complicated. Several studies have been made on the effect of multiple reflections in city street canyons by using image source methods, diffusion methods and two-dimensional wave-based numerical analysis (BEM, FDTD) [1–6].

We have examined the effect of multiple reflections on road traffic noise propagation, considering various situations of building facades and a viaduct road. From an engineering point of view, a simple calculation model for

estimating the mean increase in noise level owing to those multiple reflections have been developed. This model is based on a diffusion method and is widely applicable to almost configurations of urban roads.

In the present work, the authors intend to make a partial improvement of the calculation method discussed earlier [7] to predict the mean increase in noise level at individual receiving points. Moreover, the properties of noise propagation in a city street canyon have been investigated in a 1:40 scale model experiment [8]. The results calculated by the simple calculation model were compared with experimental data.

## 2. CALCULATION MODEL BASED ON DIFFUSION METHOD

### 2.1. Modeling Sound Propagation in Street Canyon

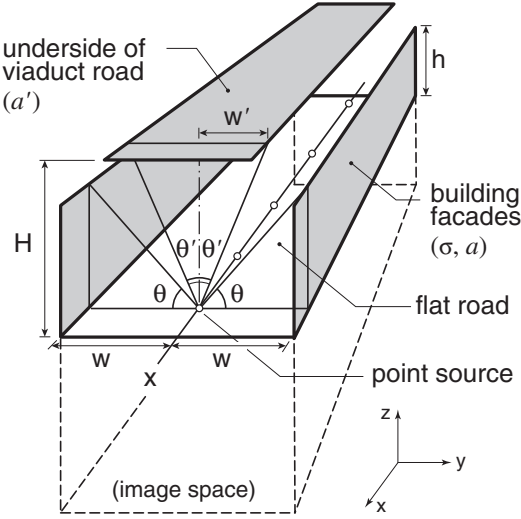
To simplify sound field modeling in street canyons that have various configurations of buildings and a viaduct road, we assumed that the street canyons may be represented by an infinite rectangular duct, as shown in Fig. 1. The walls of the rectangular duct are regarded as two parallel building facades, a flat road and the underside

---

\*e-mail: okada@ccmfs.meijo-u.ac.jp

†e-mail: yoshihisa@ccmfs.meijo-u.ac.jp

‡e-mail: kuno@aitech.ac.jp



**Fig. 1** Model geometry of idealized city street canyon with viaduct road (--- : image space considering the effect of sound reflection from the pavement of the flat road).

of a viaduct road. In this approach, it is assumed that a street canyon is a reverberant closed space with a diffuse sound field. The interference effects between the direct and reflected waves are not taken into account in the calculation.

The street width is  $2w$ , the average height of buildings is  $h$  and  $a$  is the average sound absorption coefficient of building facades. The height and width of the underside of a viaduct road are  $H$  and  $2w'$  and the average sound absorption coefficient of the underside is  $a'$ .

The acoustic power of the point source is  $P$  and the sources are located on the center of the flat road. The surface of the pavement is taken to be perfectly reflecting. The influence of the perfectly reflecting pavement can be approximated by doubling the effective source strength. The sound energy incident on the surface per unit length of a rectangular duct (street canyon) from the nondirectional point sources is given by

$$P_i = \frac{4}{2\pi} (\theta + \theta') 2\mu P \quad (1)$$

$$\theta = \tan^{-1}(h/w), \quad \theta' = \tan^{-1}(w'/H), \quad (2)$$

where  $\mu$  is the number of sources per unit length,  $\theta$  and  $\theta'$  are the angles subtended at the source by building facades and the underside of the viaduct road, respectively. The sound energy supplied by multiple reflections from those surfaces is also written by

$$P_r = \frac{4\mu P}{\pi} [\theta(1 - \sigma)(1 - a) + \theta'(1 - a')] \quad (3)$$

$$\sigma = \sum_{i=1}^n g_i/l, \quad (4)$$

where the coefficient  $\sigma$  is a parameter which represents the ratio of open space  $g_i$  to the length  $l$  of the evaluation street section in order to take into account the absorption by open spaces between buildings. This coefficient  $\sigma$  is defined as varying from 0.0 to 1.0. If buildings line both sides of the street without open spaces, the coefficient  $\sigma$  is given as 0.0.

On the other hand, the sound energy lost at those surfaces is expressed as

$$P_l = cE_r[h\sigma + h(1 - \sigma)a + (w - w') + (H - h) + w'a'], \quad (5)$$

where  $E_r$  is the energy density of the reflected sound from surfaces inside the duct. By considering that the sound energy density is the same everywhere in a diffuse field, from Eqs. (3) and (5), the energy density of the reflected sound in the street canyon is obtained as

$$E_r = \frac{16}{\pi \bar{a} l_\phi} \frac{\mu P}{c} [\theta(1 - \sigma)(1 - a) + \theta'(1 - a')] \quad (6)$$

$$\bar{a} = 1 - \frac{h(1 - \sigma)(1 - a) + w'(1 - a')}{w + H} \quad (7)$$

$$l_\phi = 4(w + H), \quad (8)$$

where  $\bar{a}$  is the average effective sound absorption coefficient of the surfaces inside the street canyon and  $l_\phi$  is the length around the cross section.

The energy density at the receiver owing to sound waves traveling along the direct path from the nondirectional sources is given by

$$E_d(y, z) = \frac{\mu P}{2c\sqrt{y^2 + z^2}}, \quad (9)$$

where  $z$  is the height of the receiver above the flat road and  $y$  is the horizontal distance between the center of the street and the receiver. Consequently, the total energy density at the receiver is obtained by the sum of the direct and reverberant components.

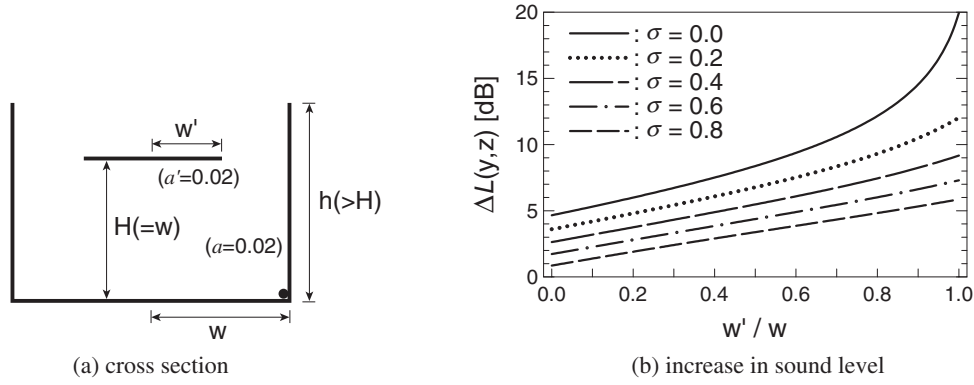
$$E(y, z) = E_r + E_d(y, z) = E_d(y, z) \left[ 1 + \frac{8\sqrt{y^2 + z^2}}{\pi(w + H)\bar{a}} (\gamma\theta + \gamma'\theta') \right] \quad (10)$$

$$\gamma = (1 - \sigma)(1 - a), \quad \gamma' = (1 - a') \quad (11)$$

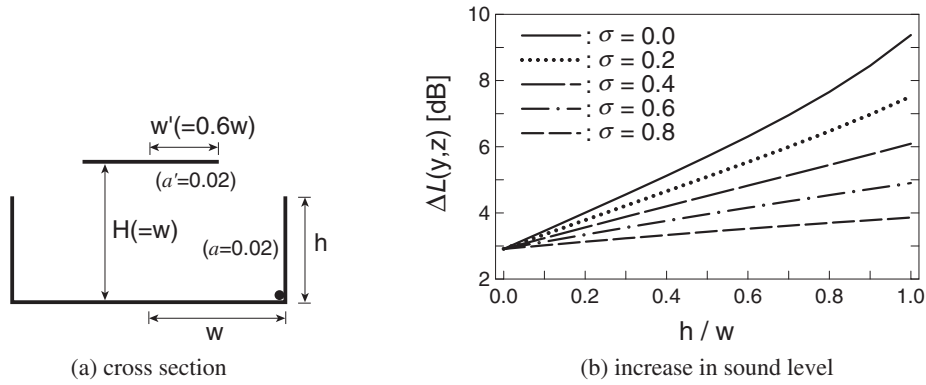
In order to estimate the effect of multiple reflections in a street canyon, we use the increase in the sound pressure level  $\Delta L(y, z)$ , which is defined as the ratio of the total energy density to the direct sound energy density, as

$$\Delta L(y, z) = 10 \log_{10} [E(y, z)/E_d(y, z)] = 10 \log_{10} \left[ 1 + \frac{8\sqrt{y^2 + z^2}}{\pi(w + H)\bar{a}} (\gamma\theta + \gamma'\theta') \right], \quad (12)$$

where, if the height  $h$  of building facades is higher than  $H$  of the viaduct road, the parameter  $h$  in Eq. (7) is replaced by  $H$ . The mean increase in the sound pressure level in



**Fig. 2** Cross section of street canyon used in the calculation and calculated increases in the sound pressure level at building facades for different viaduct road widths ( $w'$ ) and coefficients of open spaces ( $\sigma$ ).



**Fig. 3** Cross section of street canyon used in the calculation and calculated increases in the sound pressure level at building facades for different building heights ( $h$ ) and coefficients of open spaces ( $\sigma$ ).

street canyons with a viaduct road can be easily calculated from Eq. (12).

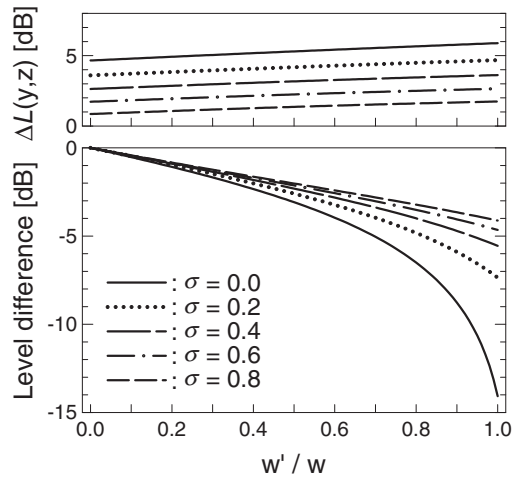
## 2.2. Calculation Results

In order to investigate the relationship between the increase in the sound level at the roadside receiver and the configuration of urban streets, the mean increases in the sound pressure level were calculated with different parameters ( $h$ ,  $H$ ,  $w'$ ) in Eq. (12). Figure 2 shows the calculated results  $\Delta L(w, z = 0)$  near the pavement in front of building facades plotted as a function of the coefficients  $w'/w$ , which is the normalized viaduct road width  $w'$  in the street width  $w$ . In this calculation, the height  $H$  of the viaduct road is lower than  $h$  of buildings and is the same as the street width  $w$ , as shown in Fig. 2(a). The average sound absorption coefficients  $a$  and  $a'$  of 0.02 are used in the calculations, assuming that the building facades and the underside of the viaduct road are reflective surfaces [9]. The results in the figure are the calculated values with coefficients  $\sigma$  in the range from 0.0 to 0.8.

The sound pressure levels increase with increases of both the viaduct road width and building density, owing to multiple reflections from building facades and the under-

side of the viaduct road. If the buildings line both sides of the street and the viaduct road is wide ( $\sigma = 0.2$ ,  $w'/w = 0.7$ ), the mean increases in the sound pressure level in front of building facades are up to almost 8 dB from that in the hemi-free field. In the typical case of an urban street in which some intersections or vacant lots exist ( $\sigma = 0.4$ ,  $w'/w = 0.6$ ), the mean increases in the sound pressure level are estimated to be almost 6 dB [10–13].

As mentioned above, the sound pressure level at the roadside receiver depends on the viaduct road widths. Next, the increases in the sound pressure level  $\Delta L(w, z = 0)$  were calculated against the heights of buildings. Figure 3 shows the calculated values plotted as a function of the coefficient  $h/w$ , which is the normalized building height  $h$  in the street width  $w$ . For this calculation, the viaduct road width becomes 0.6 times as large as the street width and the average sound absorption coefficients  $a$  and  $a'$  are 0.02, as shown in Fig. 3(a). It can be seen that the sound pressure levels increase with increasing height of buildings. However, if the coefficient  $\sigma$  is greater than 0.6, the increases in the sound pressure level in front of building facades are lower than 5 dB.



**Fig. 4** Calculated increases in the sound pressure level at building facades for absorptive surfaces ( $a' = 0.8$ ) and differences between level increases with absorptive surfaces and those with reflective surfaces ( $a' = 0.02$ ), for different viaduct road widths ( $w'$ ) and coefficients of open spaces between buildings ( $\sigma$ ).

To estimate the noise reduction effects of absorptive treatments on the underside of the viaduct road, we calculated the differences between the increases in sound pressure levels with absorptive surfaces and those with reflective surfaces. In this calculation, the absorption coefficient  $a'$  of the underside was assumed to be 0.8, even though the actual absorption coefficient depends upon the frequency and the material [14–16]. Figure 4 shows the increases in the sound pressure level  $\Delta L(w, z = 0)$  for  $a'$  of 0.8 and the differences between the level increases with absorptive surfaces and those with reflective surfaces in Fig. 2. The noise reduction effects of absorptive treatments increase with increasing viaduct road width. The effects of absorptive treatments have been estimated to be around 3 dB, when the viaduct road width is 0.6 times as large as the street width. Consequently, if suitable absorptive

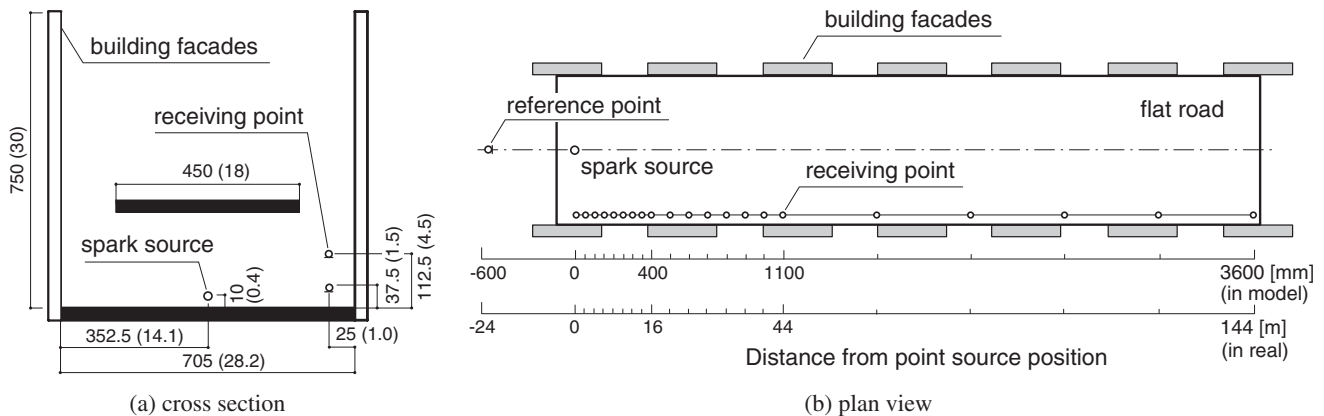
treatments on the underside of the viaduct road are adopted, the increase in the sound pressure level in built-up urban areas ( $\sigma = 0.2$ ) is estimated to be almost 5 dB, as shown in Fig. 4.

### 3. SCALE MODEL EXPERIMENT OF STREET CANYON

#### 3.1. Experimental Technique

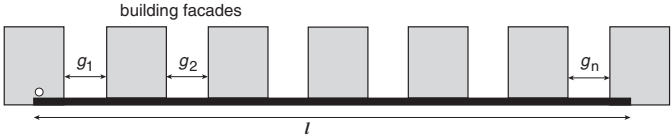
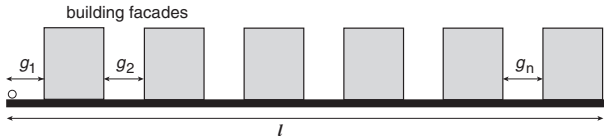
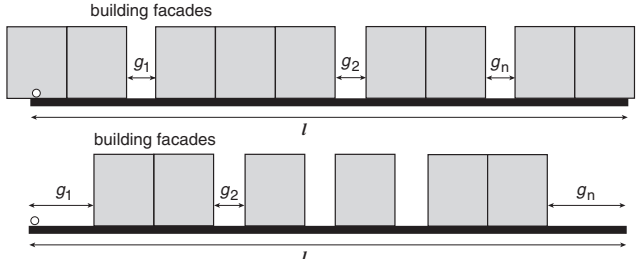
Assuming a general cross section of an urban street with four lanes, a 1:40 scale model was made. The scale model had two flat floors of a flat road and a viaduct road and two parallel walls of building facades on the flat road, as shown in Fig. 5. The model was made of rigid boards covered with a high-density polystyrene resin to ensure good reflection of sound in a wide frequency range. The length of the road was 3,600 mm (144 m in full scale) and the height of building facades was 750 mm (30 m in full scale). The flat second floor regarded as the underside of the viaduct road was located at a height of 200 mm (8 m in full scale) above the flat road. A spark source was used as a nondirectional sound source and was set at a height of 10 mm (0.4 m in full scale) above the center of the road. There were 21 receivers in a line at a distance of 25 mm (1 m in full scale) from building facades. The receivers were located at heights of 37.5 mm and 112.5 mm (1.5 m and 4.5 m in full scale, respectively). A reference microphone was also set at a distance of 600 mm from the spark source in the absence of any reflective surfaces.

The relative sound pressure level was obtained from two signals received at the reference point and each receiver, by using FFT analyzer (sampling frequency of 256 kHz, 4,096 data points). To estimate the sound pressure level of noise generated from a vehicle, the spectrum of the spark source obtained at the reference point was numerically fitted with the A-weighted sound power spectrum in 1/3 octave bands for the range of frequencies from 10 kHz to 40 kHz (250 Hz to 1 kHz in full scale) [9]. Moreover, the



**Fig. 5** Geometry of 1/40 scale model experiment. The units in the figure are millimeters and numbers in parenthesis indicate the real dimensions in meters.

**Table 1** Experimental conditions (○: spark source).

Case	Number of trials	Examples of arrangement of building facades
CASE1	12 trials	
	$\sigma = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6$ $z = 1.5, 4.5 \text{ m}$	
CASE2	12 trials	
	$\sigma = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6$ $z = 1.5, 4.5 \text{ m}$	
CASE3	22 trials	
	$\sigma = 0.1, 0.2, 0.3, 0.4$ $z = 1.5, 4.5 \text{ m}$	

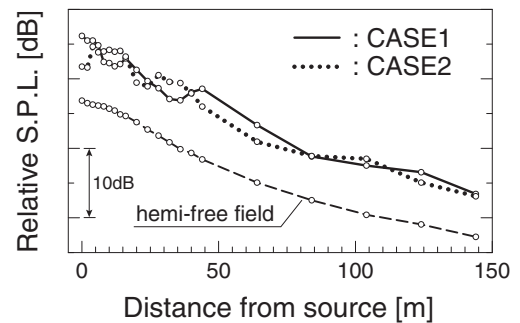
sound exposure level when a vehicle runs on the road was calculated from the relative sound pressure levels at all receiving points.

Several arrangements of building facades were selected for the experiments and a total of 46 trials, shown in Table 1, were carried out. These arrangements were divided into the following three cases: (1, 2) a building facade is or is not set at the back of receivers in the vicinity of the source and (3) building facades are arranged by considering actual urban roads. The coefficient  $\sigma$  of open spaces between building facades was calculated from the distance between building facades  $g_i$  and the length  $l$  of the model street canyon, using Eq. (4).

The sound reduction due to atmospheric absorption was not corrected, because the effect of multiple reflections was calculated from the difference between the sound exposure level in each trial and that in the hemi-free field, and the preliminary experimental results of impulse response showed that the decreases in the sound pressure level were less than 0.3 dB at distant receiving points owing to atmospheric absorption for reverberant components. Thus the effect of atmospheric absorption on the difference in the sound exposure level could be ignored.

### 3.2. Experimental Results

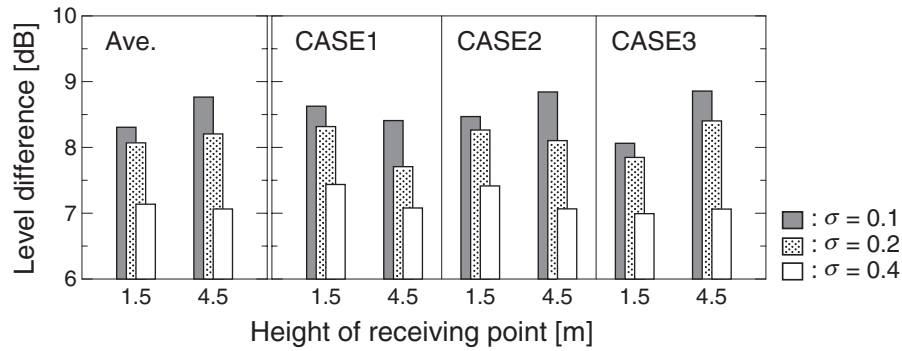
Figure 6 shows examples of the measured relative sound pressure levels plotted against the distance from the source position, when the coefficient  $\sigma$  of open spaces



**Fig. 6** Measured relative sound pressure levels in CASE1 and CASE2 ( $\sigma = 0.3$ , —: measured result in the case of sound propagation over the flat road without building facades and the viaduct road).

between building facades is 0.3 in CASE1 and CASE2, respectively. The broken line in the figure represents the reference data measured in the case of sound propagation over the flat road without building facades and the viaduct road. The sound pressure levels in the street canyon increase more than 5 dB as compared with those in the hemi-free field, even though the variations of the sound pressure levels depend on the arrangement of building facades.

The relative sound exposure levels obtained for every experiment were compared with the reference data measured in the case of sound propagation over the flat road without building facades and the viaduct road. From these

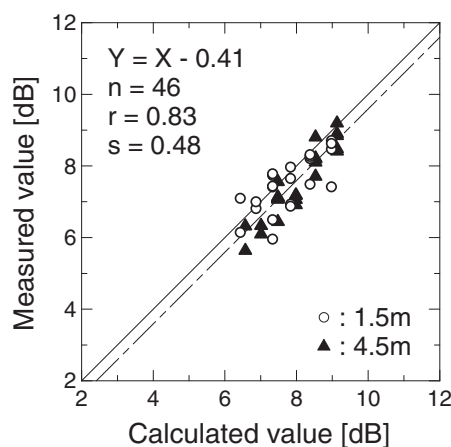


**Fig. 7** Mean sound level differences between measured sound exposure levels with the coefficient  $\sigma$  of 0.1, 0.2 and 0.4 and those in the case of sound propagation over the flat road without building facades and the viaduct road.

comparisons, the increases in the sound exposure levels owing to multiple reflections in the street canyon were estimated. Figure 7 shows the results for the coefficients  $\sigma$  of 0.1, 0.2 and 0.4, and the average level increase at each receiver height. It can be seen that the effect of multiple reflections in the street canyon increase with decreasing coefficient  $\sigma$  of the open space between building facades. For example, the mean increases in the sound exposure levels at a height of 1.5 m were 8.3 dB for the coefficient  $\sigma$  of 0.1 and 7.1 dB for  $\sigma$  of 0.4.

#### 4. VALIDATION OF CALCULATION MODEL

In order to validate the simple calculation model proposed in this paper, the comparisons between the experimental results and the values calculated in the same configuration as in the experiment were made. The sound absorption coefficients  $a$  and  $a'$  of building facades and the underside of the viaduct road were assumed to be 0.02. Figure 8 shows the calculated and measured data for all experiments. The symbols ( $n, r, s$ ) in the figure represent the number of data, the correlation coefficient and standard error, respectively. The calculated values agree reasonably



**Fig. 8** Sound pressure level increases in the street canyon for calculated and measured values ( $n$ : number of data,  $r$ : correlation coefficient,  $s$ : standard error).

well with the experimental results. Also, the relationship between the level increase and the coefficient  $\sigma$  in the calculation is similar to the tendency in the experimental results.

It can be said that the simple calculation model is useful for estimating the increases in the sound pressure level in street canyons owing to multiple reflections by building facades and the underside of a viaduct road.

#### 5. CONCLUSIONS

In urban street canyons with a viaduct road, the roadside noise level is increased by multiple reflections from building facades and the underside of a viaduct road. The authors have proposed a simple calculation model for estimating the mean increase in the sound pressure level by multiple reflections. This model is based on a diffusion method, so it can be widely applied to almost configurations of urban streets. As a result of this study, it has been found that the mean increases in the sound pressure level are estimated to be up to almost 8 dB from that in the hemi-free field, if the viaduct road is wide ( $w'/w = 0.7$ ) and the coefficient of open spaces is small ( $\sigma = 0.2$ ), such as in a built-up area.

It is concluded that the proposed calculation model is applicable to a general four-lane road surrounded with a viaduct road and high buildings. There still remain some problems in the prediction accuracy in the case of adopting noise abatement treatments on building facades or the underside of the viaduct road. Also, it is necessary to investigate the applicability of the model in an urban street with porous asphalt pavements, and to examine the applicable limits of the model by comparing calculated noise levels with those measured in actual urban streets.

#### ACKNOWLEDGMENTS

This work has been partly supported by a Grant-in-Aid for Scientific Research (No. 19560600) by MEXT, and by the work of many graduate students of Meijo University. We appreciate their assistance.

## REFERENCES

- [1] T. Le Polles, J. Picaut and M. Berengier, "Sound field modeling in a street canyon with partially diffusely reflecting boundaries by the transport theory," *J. Acoust. Soc. Am.*, **116**, 2969–2983 (2004).
- [2] K. K. lu and K. M. Li, "The propagation of sound in narrow street canyons," *J. Acoust. Soc. Am.*, **112**, 537–550 (2002).
- [3] J. Kang, "Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries," *J. Acoust. Soc. Am.*, **107**, 1394–1404 (2000).
- [4] K. V. Horoshenkov, D. C. Hothersall and S. E. Mercy, "Scale modeling of sound propagation in a city street canyon," *J. Sound Vib.*, **223**, 795–819 (1999).
- [5] J. Picaut and L. Simon, "A scale model experiment for the study of sound propagation in urban areas," *Appl. Acoust.*, **62**, 327–340 (2001).
- [6] S. Sakamoto, A. Fukushima, T. Okubo and K. Yamamoto, "Prediction of road traffic noise using two-dimensional numerical analysis," *J. Acoust. Soc. Am.*, **120**, 3334 (2006).
- [7] Y. Okada, K. Yoshihisa and K. Kuno, "Study on noise propagation in a city street canyon: Effects of reflections by building facades and the underside of an overhead road," *J. Acoust. Soc. Jpn. (J)*, **61**, 328–333 (2005) (in Japanese).
- [8] Y. Okada, K. Yoshihisa, T. Iwase and K. Kuno, "A noise prediction model in city street canyons by using a diffusion equation," *Proc. in CD-ROM of Inter-noise 2007* (2007).
- [9] Research Committee of Road Traffic Noise in the Acoustical Society of Japan, "Road traffic noise prediction model "ASJ RTN-Model 2003" proposed by the Acoustical Society of Japan," *J. Acoust. Soc. Jpn. (J)*, **60**, 192–241 (2004) (in Japanese).
- [10] Japan Road Association, *Explanation and Operation of Road Structure Ordinance* (Maruzen, Tokyo, 2004), Chap. 2, pp. 171–281 (in Japanese).
- [11] K. Fujimoto, K. Yamaguchi, T. Nakanishi and K. Anai, "Prediction of insertion loss of road traffic noise caused by detached houses in an area facing a plane road," *J. Acoust. Soc. Jpn. (J)*, **63**, 309–317 (2007) (in Japanese).
- [12] K. Fujimoto, K. Yasunaga, K. Esaki and H. Ohmori, "Attenuation of road traffic noise by detached houses," *J. Acoust. Soc. Jpn. (J)*, **56**, 815–824 (2000) (in Japanese).
- [13] K. Uesaka, H. Ohnishi, T. Chiba and K. Takagi, "Calculation methods for  $SA \cdot L_{Aeq}$  in built-up areas facing a road," *J. INCE/J*, **23**, 441–451 (1999) (in Japanese).
- [14] A. Fukushima and K. Konishi, "Noise reduction of reflected sound on the bottom of elevated road," *J. INCE/J*, **21**, 165–169 (1997) (in Japanese).
- [15] Y. Mori, "Noise reduction by absorbing panel settled under the elevated road," *J. INCE/J*, **23**, 170–173 (1999) (in Japanese).
- [16] Y. Shimizu, "Weatherproof sound absorbing materials," *J. INCE/J*, **24**, 18–20 (2000) (in Japanese).