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Revised expression of vehicle noise propagation over ground

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The authors proposed a propagation model for ground effect of vehicle noise. Since it was given by a simple formula and related charts, rough estimation of vehicle noise level at a road side could be made without any precise computation. In this paper, the model is revised for wide application to a prediction procedure of road traffic noise. Numerical expressions are given to the model by introducing a new additional parameter. The parameter, which is simply determined from the heights of a source and a receiver, is found to play an important role in the propagation model to determine the property of vehicle noise over absorptive ground. The revised expressions are applied to outdoor sound propagation on lawn field for A-weighted vehicle noise. Good agreements are obtained between calculated and experimental results. Calculation rules are empirically specified to apply our model to a prediction procedure of road traffic noise. The validity of the procedure is checked by the results of scale model experiments for typical road structures.

Keywords: Road traffic noise, Propagation, Ground effect

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1. INTRODUCTION

In prediction of road traffic noise at a road side, ground absorption is one of the most important factors that affect sound propagation from a highway to a neighboring site. The authors have proposed a model[1] for estimating excess ground attenuation for vehicle noise. The model was derived by a computer simulation based on theoretical consideration[2,3] for sound propagation with a representative spectrum of vehicle noise.[4] A mean propagation height was introduced as a parameter to the development of graphical charts for convenient treatment in the prediction procedure. However, there were still difficulties to get a value from the graphs. It was often time-consuming and troublesome, because the charts were given by curves of complicated shapes.

In this paper, a new parameter Z is introduced in setting up their numerical expressions. The parameter is expressed in terms of the heights of a source and a receiver, and it plays a reasonable role to determine the property of sound propagation over ground.

The validity of the expressions is checked by applying them to experimental results of outdoor sound propagation over lawn. Comparison is made between calculated and experimental values for broad band sound propagation of a representative A-weighted vehicle noise. Next, calculation rules are specified in order to apply the model to an actual prediction procedure for highway noise. Scale model experiments are carried out for vehicle noise propagation over absorptive ground, by setting up several standard types of highway structures. The experimental results are compared with the values calculated from the proposed prediction procedure.

2. NUMERICAL EXPRESSION OF GROUND EFFECT FOR VEHICLE NOISE

2.1 Basic Formula

Basic formula for the excess attenuation of vehicle noise in A-weighted sound pressure level is given by the following formula[1]:

$$EA=\begin{cases}-3 & \text{for } r<r_o\,,\\ -3+K\log_{10}(r/r_o) & \text{for } r>r_o\,,\end{cases} \quad (1)$$

where EA denotes the excess attenuation due to ground and r is the distance between a source and a receiver. K is a coefficient and r_o is a specific minimum distance from which excess attenuation starts to increase. Equation (1) indicates that the excess attenuation is a constant value of -3 dB up to a specified distance of r_o and then starts to increase with K dB per ten times of distance. The values of r_o and K are given by graphical charts.

2.2 Introduction of "Z" and Numerical Expression of "r_o"

The specific distance r_o is an important factor to determine the onset of the increase in excess attenuation. The distance r_o has been expressed in terms of the smaller value of either the source or the receiver height, and is given by several curves corresponding to the mean propagation height which is denoted by H_a and given by $H_a=(H_s+H_r)/2$, where H_s and H_r are the source and receiver heights, respectively. An example of the chart is shown in Fig. 1, where the effective flow resistivity of the ground is 300 kPa·s/m². The symbols on curves are the data by which the curves were delineated. Since the chart is given by various curves in limited ranges, we have to find out a suitable function to interpolate or extrapolate these curves.

After several investigations, a new parameter was found to be applicable to solve the problem. The parameter is denoted by Z and given by the following formula:

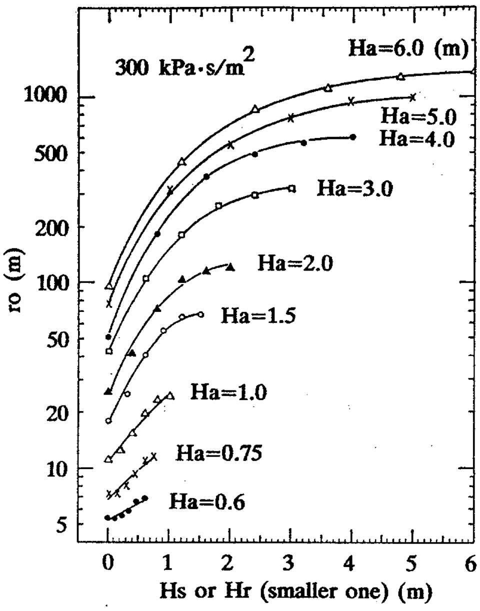

Fig. 1 Previously presented curves of r_o in the case of the ground flow resistivity of 300 kPa·s/m².

$$Z=|H_s-H_r|/(H_s+H_r)\,. \quad (2)$$

The parameter Z takes a value between 0 and 1, inclusive, and it expresses the function concerning to the geometrical arrangement of a source and a receiver above ground. For example, Z is equal to 1 when either the source or the receiver locates just on the ground, *i.e.* $H_s=0$ or $H_r=0$. The value of Z is equal to zero when $H_s=H_r$ (see Fig. 2).

The values of r_0 for 300 kPa·s/m² are plotted in terms of mean propagation height with parameters of Z, the graph of which is shown in Fig. 3. The data of r_o show linear relations with mean propagation heights on a logarithmic scale for each value of Z. The relation between r_o and H_a is expressed by the following formula:

$$r_o=A(H_a)^B\,, \quad (3)$$

where A and B are also expressed in terms of Z.

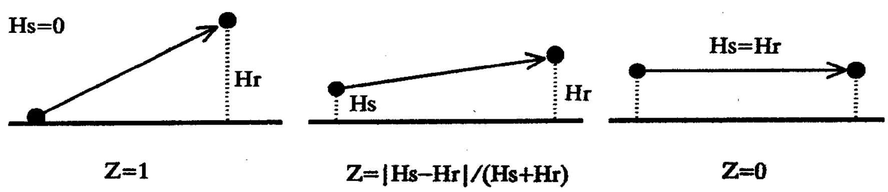

Fig. 2 New parameter Z and the geometrical arrangements of the source and receiver.

The values of A and B are determined by the least squares method and then they are approximated by the third order polynominal of the parameter Z as follows:

$$A=a_0+a_1Z+a_2Z^2+a_3Z^3, \quad (4)$$

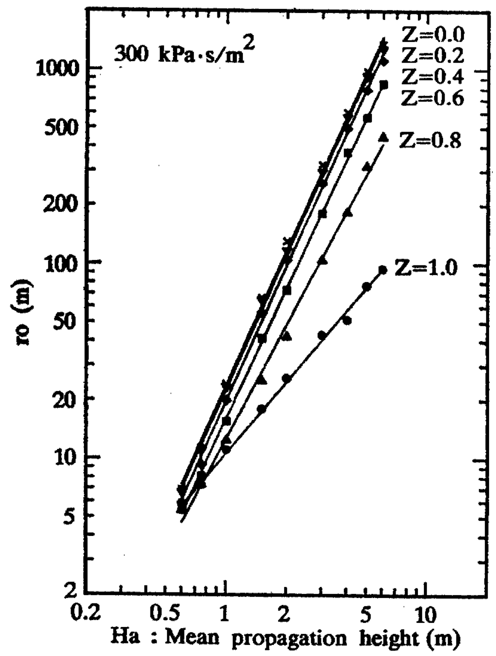

Fig. 3 Revised chart lines of r_o for the ground with effective flow resistivity of 300 kPa·s/m², which are expressed in terms of mean propagation height with parameter of Z.

$$B=b_0+b_1(Z-b)+b_2(Z-b)^2+b_3(Z-b)^3, \quad (5)$$

where $a_0 \sim a_3$ and $b_0 \sim b_3$ are regression coefficients and b is a shift value in Z. These coefficients were determined by regression analysis and the results for three types of ground, *i.e.* 75 kPa·s/m², 300 kPa·s/m² and 1,250 kPa·s/m² are shown in Table 1 for A and in Table 2 for B. As for the ground with 1,250 kPa·s/m² and for $H_a<1.1$, the data of r_o deviate from the linear relation and the exceptional expression is given as follows,

$$r_o=A(1.1)^B 10^{m(H_a-1.1)}, \quad (6)$$

where m is given by,

$$m=0.5166-0.0592Z-1.2961Z^2+1.1852Z^3. \quad (7)$$

From Eqs. (3)~(7), the relations between r_o and H_a are obtained by using the parameter Z. They are shown with the data of r_o in Fig. 3~Fig. 5 for 300 kPa·s/m², 75 kPa·s/m² and 1,250 kPa·s/m², respectively.

2.3 Numerical Expression of "K"

As for the coefficient K in Eq. (1), which was given by a graphical chart in Ref. 1), we did not revise the chart itself, but gave it a numerical expression for computation. The curve in the chart is an increasing function with respect to the mean propagation height, and it tends gradually to the value of 20. The formula for the curve is given as follows:

Table 1 Coefficients in Eq. (4) for the value A.

Ground property (kPa·s/m²)	a_0	a_1	a_2	a_3
75	35.0858	3.2582	−61.2349	30.3173
300	23.8182	1.6933	−38.1740	23.2773
1,250	18.6355	0.9456	−32.5215	32.2235

Table 2 Coefficients in Eq. (5) for the value B.

Ground property (kPa·s/m²)	b	b_0	b_1	b_2	b_3	Range
75	0	2.0900	0	0	0	$0 \leqq z < 0.4$
	0.4	2.0900	−0.1243	0.7114	−2.4719	$0.4 \leqq z < 0.8$
	0.8	1.9959	−1.7238	21.5839	−189.3597	$0.8 \leqq z \leqq 1.0$
300	0	2.3000	0	0	0	$0 \leqq z < 0.4$
	0.4	2.3000	−0.3871	0.9196	−5.4740	$0.4 \leqq z \leqq 1.0$
1,250	0	2.3000	0	0	0	$0 \leqq z < 0.2$
	0.2	2.3000	0.1697	−1.3819	−0.6479	$0.2 \leqq z \leqq 1.0$

Table 3 Coefficients in Eq. (8) for the value K.

Ground property (kPa·s/m²)	c_0	c_1	c_2	Range
75	15.0534	3.9339	0.0810	$0.6 \leqq H_a < 1.5$
	20.0	0	0	$H_a \geqq 1.5$
300	9.8545	6.9772	−0.5374	$0.6 \leqq H_a < 1.5$
	16.0167	2.4819	−1.4242	$1.5 \leqq H_a < 4.0$
	20.0	0	0	$H_a \geqq 4.0$
1,250		See Eq. (9).		$0.6 \leqq H_a < 3.0$
	15.3269	1.5282	−2.9404	$H_a \geqq 3.0$

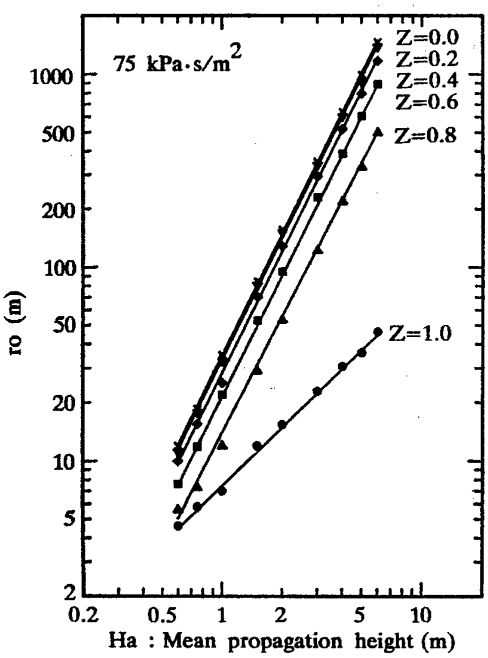

Fig. 4 Revised chart lines of r_o for the ground with effective flow resistivity of 75 kPa·s/m².

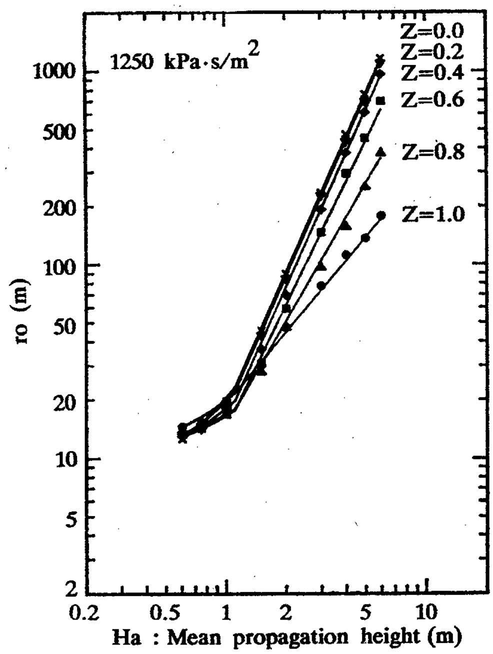

Fig. 5 Revised chart lines of r_o for the ground with effective flow resistivity of 1,250 kPa·s/m².

$$K = c_0 + c_1(H_a + c_2)^{1/2}, \qquad (8)$$

where c_0, c_1 and c_2 are regression coefficients. The coefficients determined by regression analysis are shown in Table 3. However, to get a better fitting curve, the expression for the ground with 1,250 kPa·s/m² and for $0.6 < H_a < 3.0$ is given by the next formula:

$$K = 4.9917 + 4.9750 H_a - 0.4722 H_a^2. \qquad (9)$$

The curves obtained from Eqs. (8)∼(9) and Table 3 are shown in Fig. 6 with the data of delineation.

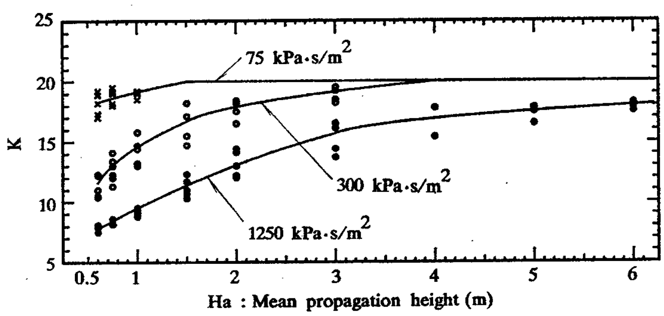

Fig. 6 Curves for the value of K. The curves are given by numerical expressions.

3. APPLICATION OF THE MODEL

3.1 Propagation of Vehicle Noise over Lawn

The authors have once carried out measurements of sound propagation on a lawn field in Tsukuba Space Center using pink noise. The mean value of sound pressure level observed with nearly zero vector wind and sound pressure level deviation due to meteorological conditions were investigated, and the results were published.[5] We tried to apply our revised model to the results of the outdoor sound propagation.

Broad band sound propagation of a representative vehicle noise spectrum (see Ref. 1)) was estimated from the measured data. A-weighted sound pressure levels were calculated from the octave band sound pressure levels at frequencies of 125 Hz to 4 kHz, by adjusting these components to fit the spectrum of A-weighted vehicle noise.

On the other hand, A-weighted sound pressure level at a receiver is calculated by the following formula:

$$L_A = L_W - 20\log_{10}(r) - 11 - EA, \qquad (10)$$

where L_A and L_W are A-weighted sound pressure level and A-weighted sound power level of the source, respectively. Equation (10) includes geometrical spreading and excess attenuation (EA) due to ground. The value of EA was computed from Eq. (1) with related equations and tables. For the ground property, an effective flow resistivity of 300

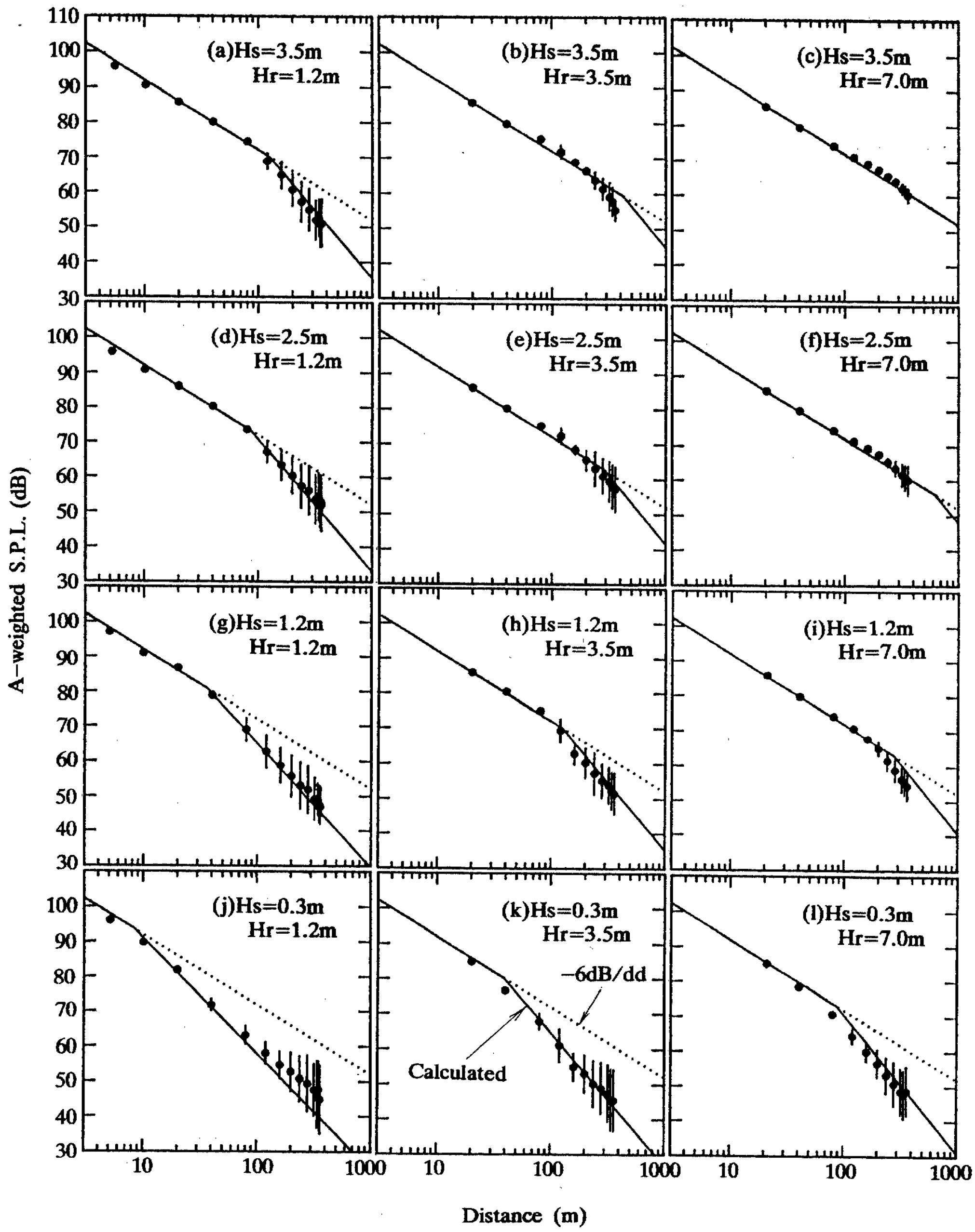

Fig. 7 Comparison of the outdoor sound propagation data and the calculated A-weighted sound pressure level.

kPa·s/m² was selected in calculation procedure, because that of the test site was estimated within the range of 200 kPa·s/m² and 300 kPa·s/m².

The experimental data of A-weighted sound pressure levels are plotted as a function of distance in comparison with the calculated values as shown in Fig. 7(a)~(l). The solid circles in Fig. 7 are the mean values of A-weighted sound pressure level out of five measurements, the bars centered at the symbols are standard deviations and the solid lines are derived from Eq. (10).

Good agreements are found between the calculated and experimental values in Fig. 7(a)~(l). The difference between the experimental data and the calculated value is close to 0 dB in average and the standard deviation is 2.2 dB for 144 data points of mean values shown in the figure. However, large sound pressure level deviations are observed at long distances. These deviations are due to the meteorological effects, the property of which was described in Ref. 5).

3.2 Application Rules in a Prediction Procedure for Road Traffic Noise

The first procedure for the prediction of road traffic noise is the calculation of a time history of A-weighted sound pressure levels from a vehicle. The time history is produced by a single vehicle moving on a highway. We can write the following formula as a basic expression for each sound level component of the history:

$$L_A = L_W - 20\log_{10}(r) - 8 + C_d + C_g\,, \qquad (11)$$

where terms C_d and C_g are corrections for diffraction effect and ground attenuation, respectively. Since the expression is formulated for sound propagation in hemi-free field, the constant value of -8 dB is given in the formula instead of -11 dB. In order to apply our ground effect model to the correction term C_g in Eq. (11), an adjustment of 3 dB and a change of sign are made to EA in Eq. (1). As a result, the expression for C_g is expressed by,

$$C_g = \begin{cases} 0 & \text{for } r < r_o \\ -K\log_{10}(r/r_o) & \text{for } r > r_o \end{cases}, \qquad (12)$$

where K and r_o are given in Eq. (1). On the other hand, the correction term C_d is generally given as the sound attenuation when an acoustical obstacle or a barrier is presented along the highway.

In applying the ground effect to the prediction procedure of a real situation, there are some rules to be specified. One is for the discontinuity of ground impedance and the other is for the coupling between the ground effect and the diffraction effect. These effects were theoretically treated by Takagi[6] for the calculation of noise propagation from highway structures. However, we will have to set up an empirical rule to our practical method to deal with these problems.

As for the discontinuity of ground impedance, we treated the sound propagation from acoustically hard surface to soft surface, *i.e.* from asphalt to absorptive ground. Since asphalt is regarded as a rigid and reflective surface, the broad band sound such as vehicle noise does not decrease by excess attenuation during propagation. The attenuation due to ground will appear after transmitted into the absorptive ground area. We specified a distance of r_a as a sound path over asphalt (see Fig. 8), and assumed the next conditional formula for correction term C_g,

if $r_a > r_o$, then

$$C_g = \begin{cases} 0 & \text{for } r < r_a \\ -K\log_{10}(r/r_a) & \text{for } r > r_a \end{cases}. \qquad (13)$$

This equation is obtained by replacing r_o in Eq. (12) by r_a, which means that the onset of ground attenuation is shifted from r_o to r_a. As for $r_a < r_o$, the correction is given by Eq. (12).

The coupling between the ground and diffraction effects is generally a phenomenon that the sound attenuation due to ground is replaced by the attenua-

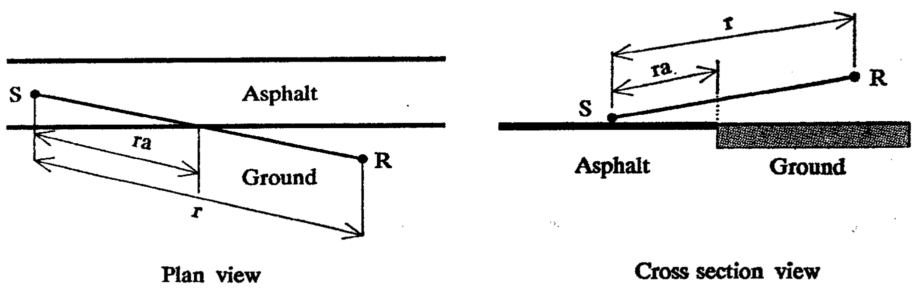

Fig. 8 Specific distance of "r_a."

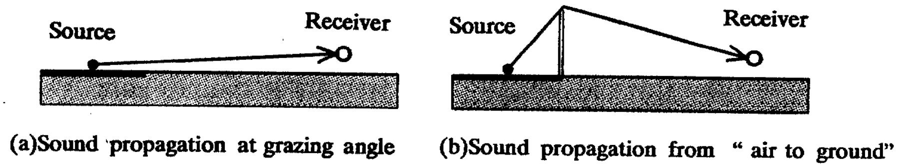

Fig. 9 Change in sound path for the cases with and without a barrier. Case (a) has a large effect due to ground, while the ground effect is decreased by the installation of the barrier in case (b).

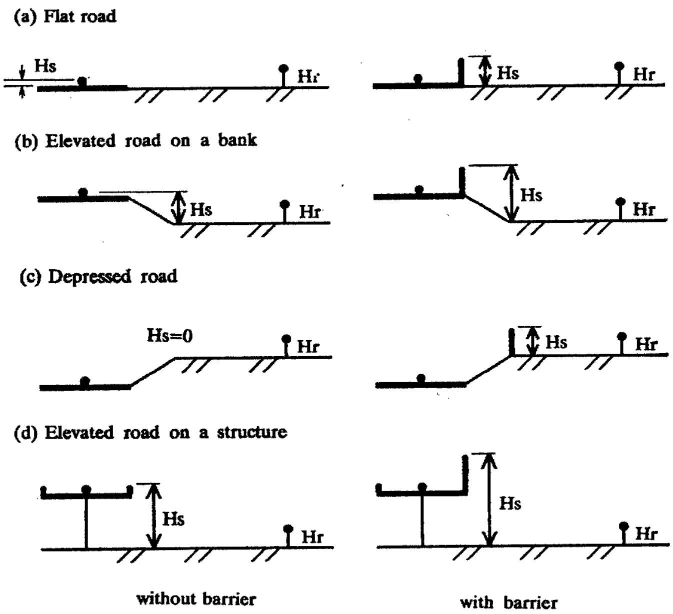

Fig. 10 Specification of effective source height for representative road structures with and without barrier.

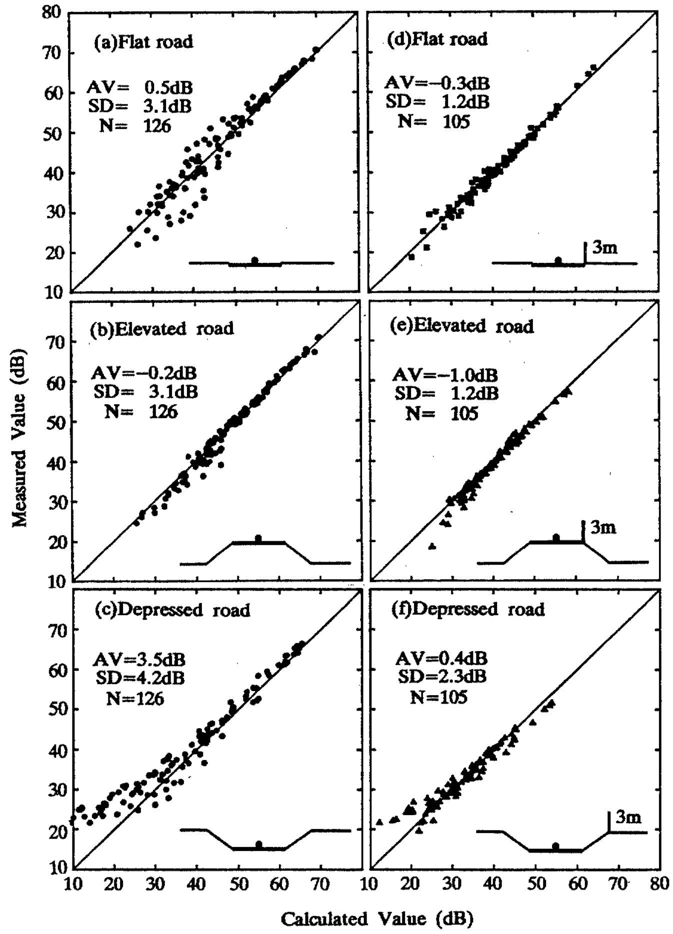

Fig. 11 Comparison of the data from scale model experiment and the calculated A-weighted sound pressure level. The term AV and SD denote average and standard deviation of the difference between the calculated and measured values. The term *N* is the number of the data.

tion due to acoustical barriers or obstacles. Let us suppose an installation of an acoustical barrier at a side edge of a flat road. The barrier installation will change the direction of sound propagation from grazing angle to, so called, "air to ground" (see Fig. 9). It is obvious that installing a barrier gives increase in noise attenuation due to shielding effect, while the ground attenuation is reduced because the effective height of the source is raised to the top of barrier. Considering this coupling, we may specify the effective height of a source for the calculation of ground attenuation. Typical examples are shown in Fig. 10 for the effective source height in the various cases of road structures.

3.3 Scale Model Experiments for Various Types of Highway

In order to investigate the validity of the calculation procedures mentioned above, scale model experiments[7] were carried out. The scale factor was 1/50. Three types of road structure were considered. They were a flat road, an elevated road on a bank with a height of 2.3 m and a depressed road, which is 7 m below the ground, with 45 degree inclined retaining wall. The ground, outside of the road surface of 25 m in width, was simulated as an absorptive surface with an effective flow resistivity of 300 kPa·s/m².

Microphones were located in a straight line at 0 m, 10 m, 20 m, 40 m, 80 m and 160 m from the road edge and their heights were 1.2 m, 3.5 m and 7 m above the ground. A point source of jet noise type was used in the scale model to simulate a single vehicle. The source was placed at a height of 0.3 m above the road surface and moved along the center line of the road. The source positions were at 0 m, 12.5 m, 25 m, 50 m, 100 m, 200 m and 300 m from the intersection of the center line of the road and the line of microphone arrangement. The sound received at each microphone was analyzed to obtain 1/3 octave band sound pressure levels. Relative A-weighted sound pressure level was obtained by adjusting the power spectrum of the source to that of the representative vehicle noise.[1]

The comparisons between the experimental results and the calculated values are shown in Fig. 11(a)~(f), where the figures (a)~(c) are for the cases without barrier and the figures (d)~(f) are with a barrier of 3 m height. The calculated values were obtained by setting the power level to that of a vehicle noise source in the experiment. The term C_d was calculated from Maekawa's chart[8] by specifying the representative frequency as 700 Hz. The frequency was selected as a predominant frequency in the representative spectrum expected behind a barrier.

The experimental results show good agreements with the calculated values for all types of road with barrier and for elevated road without barrier. However, a little deviation is seen in the data for flat and depressed road without barrier. The deviation increases at the area far from the source, where the calculated sound pressure level is comparatively low. It seems that the disagreement appears where the ground attenuation is relatively dominant over the attenuation due to diffraction effect.

4. DISCUSSION

The results in Fig. 7 show the validity of the revised expression in the estimation of ground effect for vehicle noise. However, the standard deviations of the experimental data increase with distance. Since outdoor sound propagation is strongly affected by meteorological conditions as well as ground property, the amount of the sound level variation has to be investigated and reasonably taken into account in the prediction procedure in the future. Moreover, a limit of excess attenuation has to be introduced for reasonable prediction.

The term C_d in Eq. (11) is estimated from Maekawa's experimental chart. Since it is given for diffraction effect of a thin screen, the use of this chart seems unreasonable to apply to wedge diffraction in the case of elevated or depressed roads without noise barrier. The wedge diffraction effect depends strongly upon the acoustical property of wedge surface.

In the case of a reflective wedge, experimental data, which are not shown here, showed 1 dB higher than calculated values in average for an elevated road and 4.5 dB higher for an depressed road. In the latter case, sound built-up due to multiple reflection between retaining walls might become an additional effect to wedge diffraction. The reason why the experimental values in Fig. 11 agreed by chance with the calculated values by a thin screen might be due to the absorptive property of the wedge surface.

Considering the good results in Fig. 11, we may say the specification of the empirical rules is reasonable, *i.e.* the treatment of the asphalt to absorptive ground propagation, the specification of the effective source height in Fig. 10, and also the treatment of the diffraction for road structures.

5. CONCLUDING REMARKS

By introducing a new parameter of Z which represents the geometrical arrangement of a source and a receiver above ground, a revised model of ground effect has been derived for vehicle noise. It was applied to the outdoor propagation of A-weighted vehicle noise over lawn and reasonable agreement has been obtained. The application rules have been empirically established for the discontinuity of ground impedance and the coupling between ground and diffraction effects. The validity of the rule has been checked by applying the procedure to the results of scale model experiments for representative road structures.

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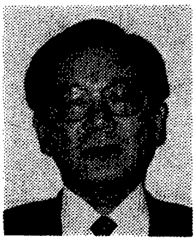

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