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THE ACOUSTIC PERFORMANCE OF AN INCLINED BARRIER FOR HIGH-RISE RESIDENTS

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The objective of this paper is to develop a scale model to analyze the performance of the inclined barrier design. A computer program was used to outline the zone of noise variation with the tilted angle of a barrier. The results of this study show that the average noise level at lower receivers behind the nearside barrier could be reduced by 4, 6 and 10 dB for 125, 250 and 500 Hz, respectively, by tilting the angle of the farside barrier by over 10°. This result seems to be sufficient to counteract the reflected noise problems at lower receivers. It is also noted that degradation is smaller for low frequency. The simple image source and virtual barrier model computer program can help us to locate the critical reflection zone with different tilted angles of the barriers. Based on the image source model, appropriate improvements of inclined barrier can be designed easily by using geometrical drawings without calculation.

1. INTRODUCTION

In an urban townscape, it is inevitable that buildings are built close to the traffic road due to the scarcity of land. Barriers are often placed on the roadside for controlling traffic noise. Normally, about 5–10 dB (A) insertion loss is expected at nearby locations [1]. However, the performance of a barrier is not as good as we anticipated when parallel barriers are placed on the opposite sides of highways.

A detailed examination of the literature on the multiple reflection effect in parallel barriers has shown a significant increase of noise in the screened area of the first barrier due to reflection effect [2, 3]. Many aspects of the problem have been studied and a number of measures have been suggested, such as reducing the reflection effect by using sound-absorptive material [4]. However, if a barrier is erected with absorptive material, the initial cost and the maintenance cost will be high and the maintenance will be difficult and no material can provide a fully absorptive performance at all frequency bands. Highway engineers find it very difficult to compromise between the acoustic and the durability requirement.

Inclined barrier [3, 5] is one of the ways to reduce the reflection effect but it is not very useful for high-rise buildings. The calculation of road traffic noise [6] by the UK Transport Department assumes, when the inclined angle is greater than 15°, that the reflection effect is not affected by the barrier height. A recently available computer program [7] did not provide a straightforward design rule and does not consider the frequency spectrum. Cianfrini *et al.* [8] used theoretical analysis of the acoustical behavior of diffusive reflection in parallel roadside barriers but the model was very complicated.

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In view of this, the objective of this paper is to develop a model to analyze the effects of reflection on the performance of the inclined barrier design. The basic concept is that on inclining a barrier on one side, the power of multiple reflections and the diffuse energy components will decrease. A computer program was also used to outline the zone of noise variation with the tilted angle of barrier. The mathematical theories of the single-barrier prediction are based on Maekawa's prediction [9], which predicts the attenuation produced by the barrier as a function of geometry and frequency. Lam [10] has also used Maekawa's empirical curve and model experiments to estimate the attenuation associated with each diffracted path but he did not consider the reflection effects. In this study, the single-image source concept was used for estimating the reflection effect of the second barrier. The basic principle of the single-image source assumes that the reflection source is directly emitted from the optical image of the primary source and only the first order reflection is considered.

1.1. BASIC THEORETICAL MODEL FOR NOISE DISTRIBUTION AT SINGLE AND PARALLEL BARRIER

Figure 1 shows the cross-section of a traffic road to illustrate the way in which traffic noise is reflected and diffracted to the receivers.

Figure 1(a) shows a single-reflective barrier placed on the edge of the traffic road and the shadow zone. Within the shadow zone, the barrier effectively obstructs the direct source and noise mainly diffracts over the top of the barrier giving, at least 5 dB noise reduction [6].

In Figure 1(b), parallel reflective barriers are placed on both sides of the traffic road. The performance of the barrier is reduced due to noise reflection from the farside barrier. The reflection effect can be simply explained in terms of an image source placed behind the farside barrier. Degradation is most significant in the intersecting region of the illuminated zone of the virtual source and the shadow zone of the real source (Z2). This model had been successfully used for train and traffic noise [11, 12].

In Figure 1(c), parallel reflective barriers are placed on both sides of the traffic road. The farside barrier is tilted outward to the traffic road. The zone of reflection from the second barrier (Z1) extends and shifts to a high level. The degradation of insertion loss at the low receiver reduces but increases at the high receiver.

The noticeable features in parallel barrier are:

(1) $Y < Ys2$: Receiver within the shadow zone of both the virtual and the real source. The degradation is small at the lower part but increases as Y is close to $Ys2$ by diffraction.

(2) $Ys2 < Y < Ys$: Receiver above the shadow zone of the virtual source but within the shadow zone of the real source. Degradation due to the multiple reflection from the opposite barrier is very significant.

(3) $Y > Ys1$: Receiver within the shadow zone of the virtual source but above the shadow zone of the real source. Propagation from the virtual source is much attenuated by distance. Degradation due to the opposite barrier is minimal.

1.2. PREDICTION MODEL

A large number of computer models have been developed to estimate the insertion loss and the reflection effect of noise barriers in the past. Most of these computer models can accurately predict the noise reduction from source to receiver by noise barriers, but these

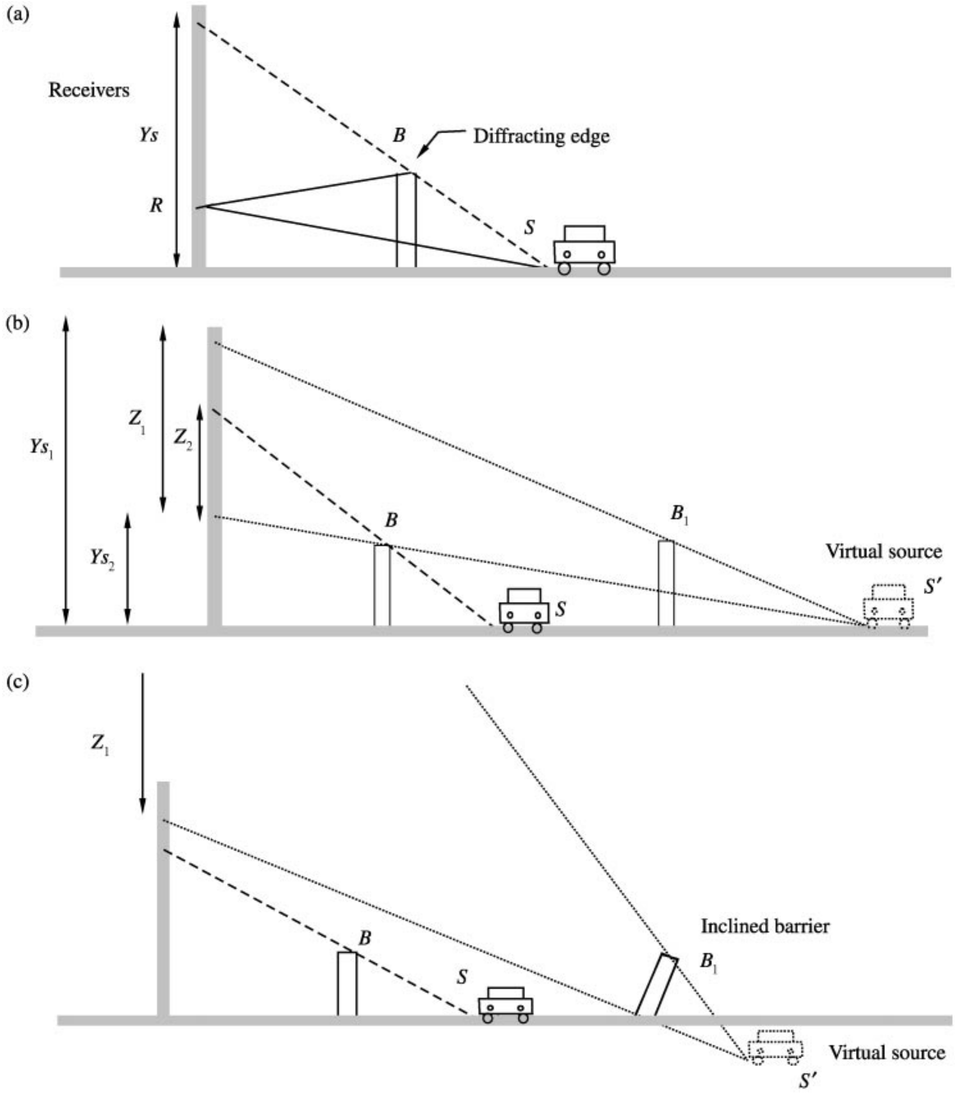

Figure 1(a). Single barrier (b) parallel barrier (c) inclined barriers: -----, separate the illuminated zone and shadow zone, the region below this line is considered as shadow zone; ······, between these two lines is the reflective zone, the source will be directly reflected from the farside barrier to the receiver behind the nearside barrier.

are rather complicated and a long time is required for entering the site boundary details and the traffic flows condition. Also, they are easily used for design optimization purposes.

In this paper, a simple model was developed. The mathematical theories of the single barrier prediction are based on Maekawa's prediction [9], which predicts the attenuation produced by the barrier as a function of geometry and frequency. The reflection effect of the second barrier is estimated by assuming that an equivalent image source replaces the walls, with the single real source situated between parallel reflecting walls. The advantage of using this model is that it is easier to identify the region of the critical reflection zone from the second barrier. These data can provide engineers with the basic information about the reflection effect and the design of corresponding noise abatement measure.

1.2.1. *Prediction of insertion loss* (*Figure* 1(*a*))

The Maekawa prediction is in terms of the Fresnel number N given by

$$N = \frac{2\delta}{\lambda}, \tag{1}$$

where the path difference, δ, the difference between the shortest path over the barrier and the direct path, is given by

$$\delta = SB + BR - SR \tag{2}$$

and λ is the wavelength.

As given in reference [1], when $Y > Ys$ (illuminated region), the barrier attenuation ΔL_0 is given by

$$\Delta L_0 = 0\,\mathrm{dB}, \qquad N' > 1.0972,$$

$$\Delta L_0 = -\left[5 + 20\log\left(\frac{N'}{\tan N'}\right)\right]\mathrm{dB}, \quad \text{for } N' \leqslant 1.0972. \tag{3}$$

where $N' = (2\pi N)^{0 \cdot 5}$. When $Y \leqslant Ys$ (shadow region), then

$$\Delta L_0 = -\left[5 + 20C_1\log\left(\frac{N'}{\tanh(C_2N')}\right)\right]\mathrm{dB} \quad \text{for } N' \leqslant 10 \tag{4}$$

$\Delta L_0 = -\ 20\,\mathrm{dB}$ for $N' > 10$.

The coefficients C_1 and C_2 modify the size of the source. In this program, a line source is used: $C_1 = 0.75$ and $C_2 = 1.00$.

Attenuation due to distance is

$$L = -\ 10\log_{10}\left(\frac{SR}{13.5}\right). \tag{5}$$

The total noise reduction from S to R is

$$L_0 = L + \Delta L_0. \tag{6}$$

1.2.2. *Prediction of Reflection by the Image Source Model* (*Figure* 1(*a*) *and* 1(*b*)

Due to the existence of two shadow zones (arising from the first barrier and the virtual barrier), the virtual source produces two critical values $Ys1$ and $Ys2$, and the two path differences

$$\delta_1 = S'B + BR - S'R, \tag{7}$$

$$\delta_2 = S'B1 + B1R - S'R. \tag{8}$$

Let

$Yz = (Ys1 + Ys2)/2$, if $Yz \geqslant Y$ then $\delta = \delta_1$ else $\delta = \delta_2$.

When $Y \geqslant Ys1$ or $Y < Ys2$, the barrier attenuation ΔL_1 is given by equation (4) above. When $Ys1 \geqslant Y > Ys2$, ΔL_1 is given by equation (3) above.

Combining the distance and the barrier effect, the total attenuation due to the second barrier is

$$L_1 = -10\log_{10}\left(\frac{S'R}{13.5}\right) + \Delta L_1. \tag{9}$$

Then the new attenuation due to the two barriers is

$$L_2 = 10\log_{10}(10^{L_0/10} + 10^{L_1/10}). \tag{10}$$

The degradation due to the second barrier is

$$D = L_2 - L_0. \tag{11}$$

1.3. METHODOLOGY OF SCALE MODEL TEST

In order to verify the accuracy of the result from the theoretical prediction model, a scale model was used to compare the result by the theoretical model prediction.

The test focused on the reflection effect by the second-barrier erection. It was undertaken in a semi-anechoic room to simulate the free field conditions and to reduce the unwanted reflection. To reduce the uncertain parameters in the test, the nearside barrier was replaced by an absorptive partial enclosure that could minimize the noise from the source arriving directly at the receiver so that the reflection from the virtual source became dominant.

A 1 : 20 scale model was used. The noise source was generated by 12 loudspeakers which were connected to two different signal generators and contained in a rectangular box with an air gap of 25 mm × 2.2 m at the bottom (see Figure 2(a)). The sources face the floor. The advantage of doing this is to enhance the multiple reflection between the speakers and the floor. It generated a diffused source from the gap and reduced the directional effect. Preliminary measurements were undertaken surrounding the source to ensure that the sound source was really diffuse.

To minimize the noise interference from these loudspeakers, they were installed at different orientations in the box and every alternative loudspeaker was connected to a signal generator to ensure that the signal generated from the loudspeaker was different from the previous one. The benefit of using loudspeakers as a noise source is that loudspeakers can provide a stable line source.

The farside barrier was made of cardboard and covered by 0.5 mm thick stainless steel to ensure that a totally reflective surface was provided. The absorptive partial enclosure was made of cardboard and vinyl to increase sound insulation. The interior of the enclosure was lined with an absorber to reduce its reflective properties. The height is of both the barriers and the enclosure for studies were 6 m and four angles of incidence of the farside barrier were analyzed: 0, 10 and 15° [see Figure 2(b)].

The noise source signal was white noise with the frequency ranged from 1 to 12.5 kHz. The frequencies of 2.5, 5 and 10 kHz that are simulation of the (125, 250 and 500 Hz) dominant traffic noise frequency, were measured for analysis. Before the measurement, the two signal generators were adjusted to a similar level at all specific bands and it was ensured that the noise source was at least 30 dB above the background for each one-third octave band in the range of interest.

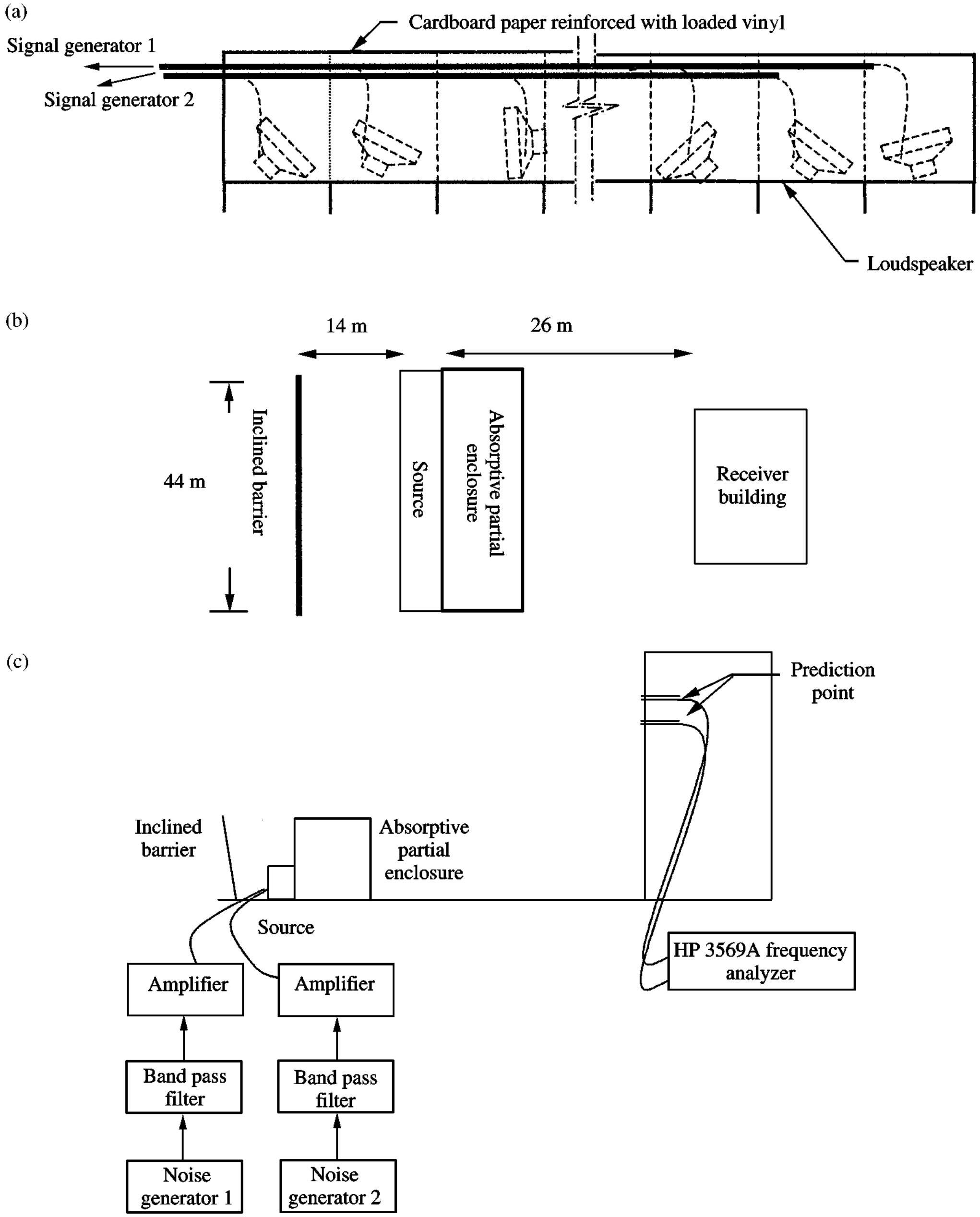

Figure 2(a). Detail drawing of rectangle loudspeakers. (b) Plan view of model. (c) Elevation of inclined barrier model.

The measurement was taken for a 1 min period at two positions behind the barrier and was analyzed by an HP 3569A real-time frequency analyzer [see Figure 2(c)]. Another sound level meter was used for measurement throughout the testing period, to monitor the sound level generated which has been found to vary within ±1 dB.

2. RESULTS OF TEST AND MODEL

The efficiency of noise reduction by vertical parallel barriers (conventional) was compared with that of the inclined barriers. Figure 3(a) shows the variation of degradation of insertion loss at different heights of receiver by the second barrier of angle 0° for 125, 250 and 500 Hz. In this testing condition, about 10 dB of degradation for 500 Hz was increased as the height of receiver increased from 5 to 12 m above the ground. Afterwards, the degradation shows a very insignificant decrease with increasing height, of less than 3 dB from 12 to 19 m for 500 Hz. The degradation considerably decreases as the height of receiver increases from 19 to 33 m. The theoretical reflection zone concept can be used to explain these degradation variations. The theoretical reflection zone located between lines $Ys1$ and $Ys2$ which are close to the critical reflective areas measured by the scale model. In this region, the noise reflected from the opposite barrier can be considered as being emitted directly from the image source. Outside this region, the noise reflected from the opposite barrier is attenuated by barrier effects and the degradation effect becomes lower. In this test, the reflection zone is 9–20 m high from the ground level ($Ys2$ to $Ys1$) and the degradation of insertion loss is up to 16 dB.

In Figure 3(b) and (c), the farside barrier is tilted 10 and 15° to the traffic road, respectively. It can be seen that the trend of degradation of insertion loss by the second barrier shifts to the right-hand side and the reflection zone is moved to a higher level, the lower receiver can get a noticeable improvement. However, a problem arises at the higher receivers; the noise level becomes more than 10 dB above the conventional condition.

A comparison of the theoretical model and the scale model is shown in Figure 4. In these figures, the noise variation at receivers of different heights by different inclined angles of the second barrier can be seen. In Figure 4(a), the absolute noise level of receiver behind the nearside of vertical parallel barriers was plotted. Figure 4(b) and 4(c) shows the absolute noise value of receivers behind the nearside barrier when the second barrier is inclined at 10 and 15°, respectively. The trends of theoretical degradation are in agreement with those of the scale model.

The computer programs can plot the noise variation behind the first barrier by changing the tilted angle of second barriers and are shown as noise-level contour maps in

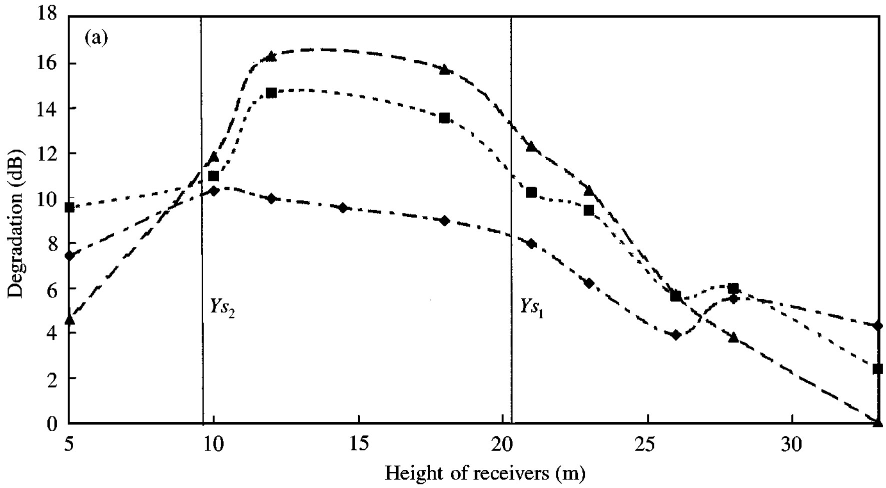

Figure 3(a). Degradation of insertion loss by the parallel barrier: angle of nearside barrier = 0°, farside barrier = 0°. Measurement is undertaken in 1 : 20 scale model: $Ys1$ = 20·1 m, $Ys2$ = 9·3 m. -◆-, 125 Hz; -■-, 250 Hz; -▲-, 500 Hz.

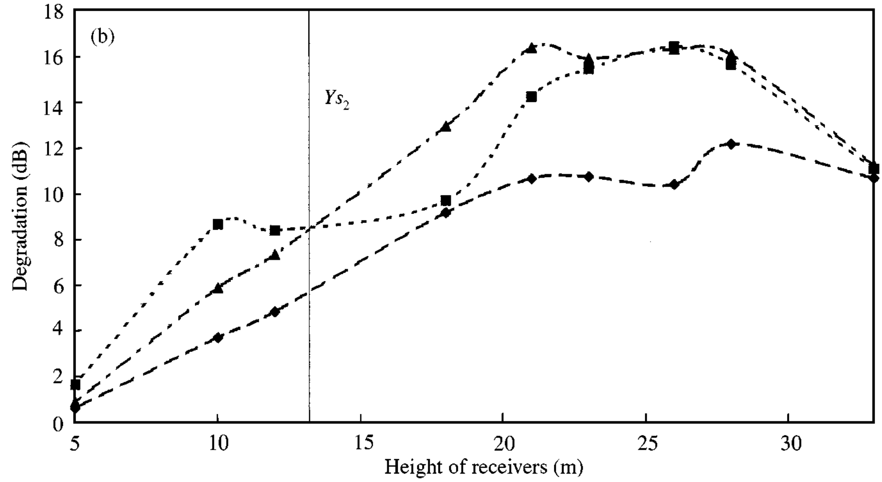

Figure 3(b). Degradation of insertion loss by parallel barriers: angle of nearside barrier = 0°, farside barrier = 10°. Measurement is undertaken in 1:20 scale model: $Ys1 = 37{\cdot}4$ m, $Ys2 = 13{\cdot}0$ m. -◆-, 125 Hz; -■-, 250 Hz; -▲-, 500 Hz.

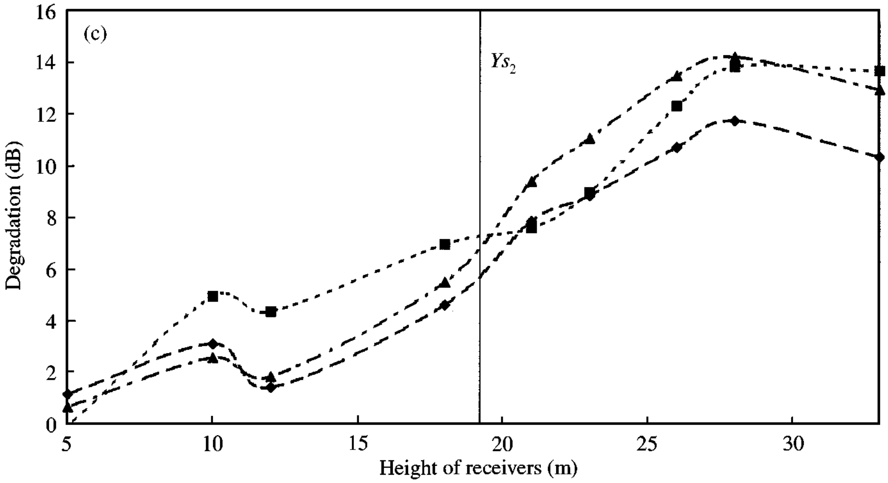

Figure 3(c). Degradation of insertion loss by parallel barriers: angle of nearside barrier = 0°, farside barrier = 15°. Measurement is undertaken in 1:20 scale model: $Ys1 = 50{\cdot}2$ m, $Ys2 = 19{\cdot}6$ m. -◆-, 125 Hz; -■-, 250 Hz; -▲-, 500 Hz.

Figures 5 and 6. In these figures, we can see that the noise variation by changing the angle of the tilt barrier at 125 Hz was not as high as that at 500 Hz frequency band when parallel barriers are placed. By the equation $C = f\lambda$ the speed of sound is around 340 m/s, the wavelength of 125 and 500 Hz is 2.72 and 0.68 m, respectively. The shorter the wavelength, the less will be the diffraction effects. The general behavior of high-frequency sound wave transmission is a straight line propagation and similar to that of the light ray. The incident angle is almost identical to the reflective angle when the wave reaches the barrier. However, the low-frequency sound waves such as 125 Hz are not reflected like the optical reflection. Due to edge effects, parts of sound waves are diffracted from the top of barrier and the

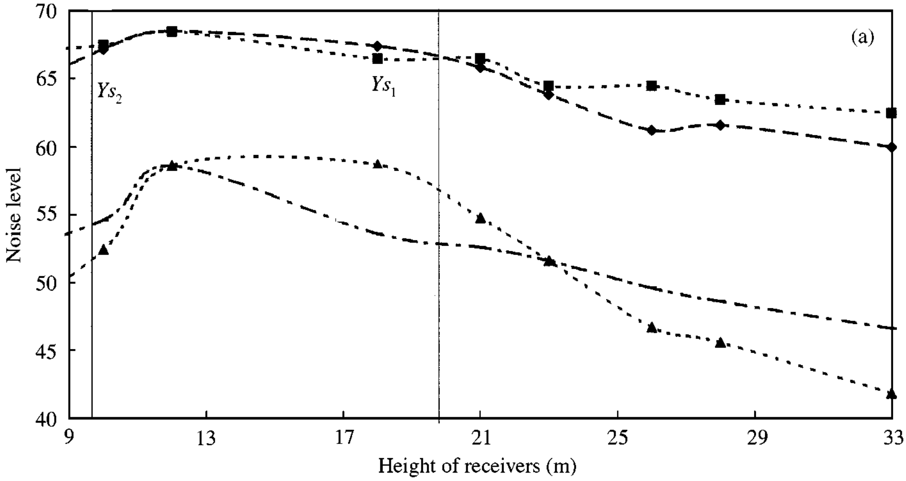

Figure 4(a). Noise variation at different heights of receivers: angle of nearside barrier = 0°, farside barrier = 0°, $Ys1 = 20{\cdot}1$ m, $Ys2 = 9{\cdot}3$ m. -◆-, computer model (125 Hz); -■-, scale model (125 Hz); -▲-, scale model (500 Hz); — — —, computer model (500 Hz).

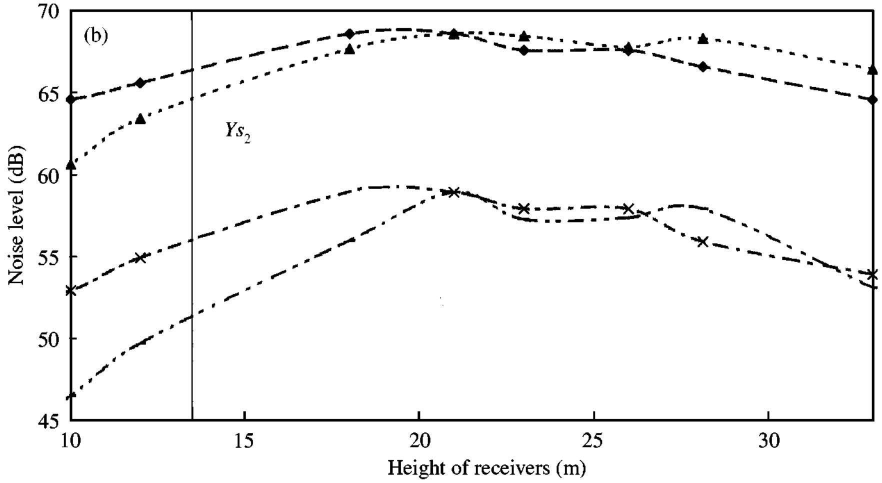

Figure 4(b). Noise variation at different heights of receivers: angle of nearside barrier = 0°, farside barrier = 10°, $Ys1 = 37{\cdot}4$ m, $Ys2 = 13$ m. -▲-, computer model (125 Hz); -◆-, scale model (125 Hz); — — —, scale model (500 Hz); -×-, computer model (500 Hz).

power of reflection is relatively less. In practice, the above phenomenon can be explained by the lower sound attenuation of barrier at low frequency due to higher diffraction effects.

2.1. ANALYSIS OF RESULTS

(1) *Comparison with CRTN prediction method.* This prediction assumes, when the inclined angle is greater than 15°, that the reflection effect is not affected by the barrier height and the degradation due to reflection is about 1·5 dB. However, this assumption is not in

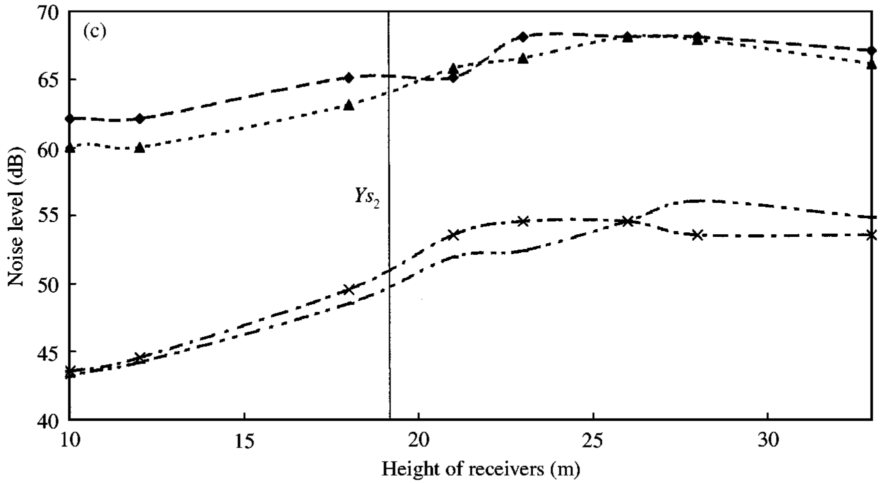

Figure 4(c). Noise variation at different heights of receivers: angle of nearside barrier = 0°, farside barrier = 15°, $Ys1 = 50·2$ m, $Ys2 = 19·6$ m. -▲-, computer model (125 Hz); -◆-, scale model (125 Hz); ▬ ▬ ▬, scale model (500 Hz); -×-, computer model.

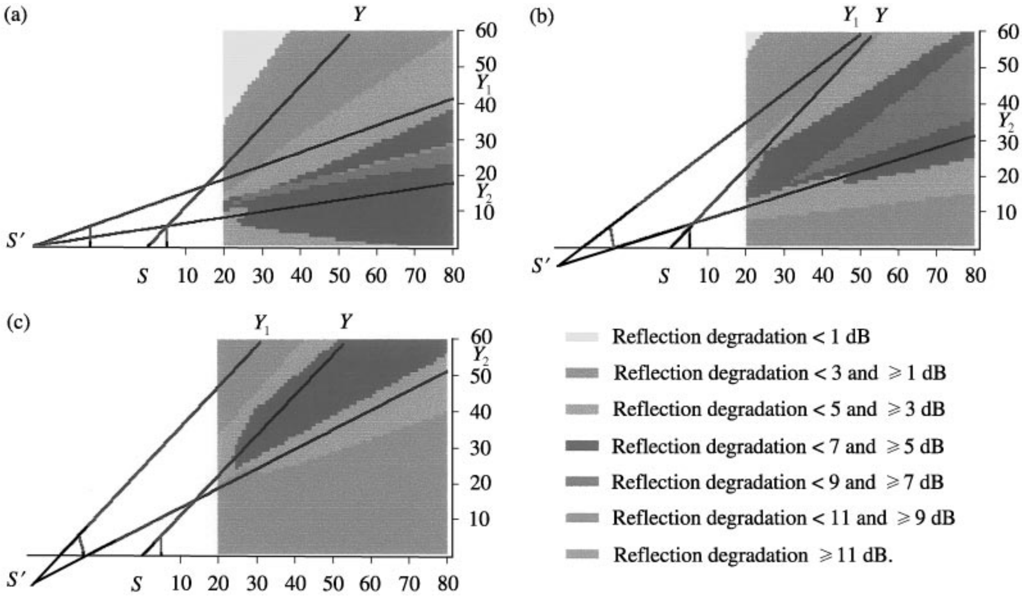

Figure 5. Noise variation behind the first barrier for tilt angle of second barrier: The distance from the source to the nearside barrier = 5 m, frequency for analysis = 125 Hz; The height of nearside barrier = 6 m, height of farside barrier = 6 m; The Horizontal distance between the barrier = 20 m; and tilted angle of farside barrier (a) = 0°; (b) = 10°; (c) = 15°.

agreement with the scale model result. From Figure 3(c), it can be seen that the degradation is small until it reaches 14 m, the degradation value rises to 10 dB.

(2) *Region of degradation.* Degradation is the most significant in the region where the illuminated zone of the virtual source and the shadow zone of the primary source overlap (between $Ys1$ and $Ys2$). When the inclined angle of barrier increases, the critical

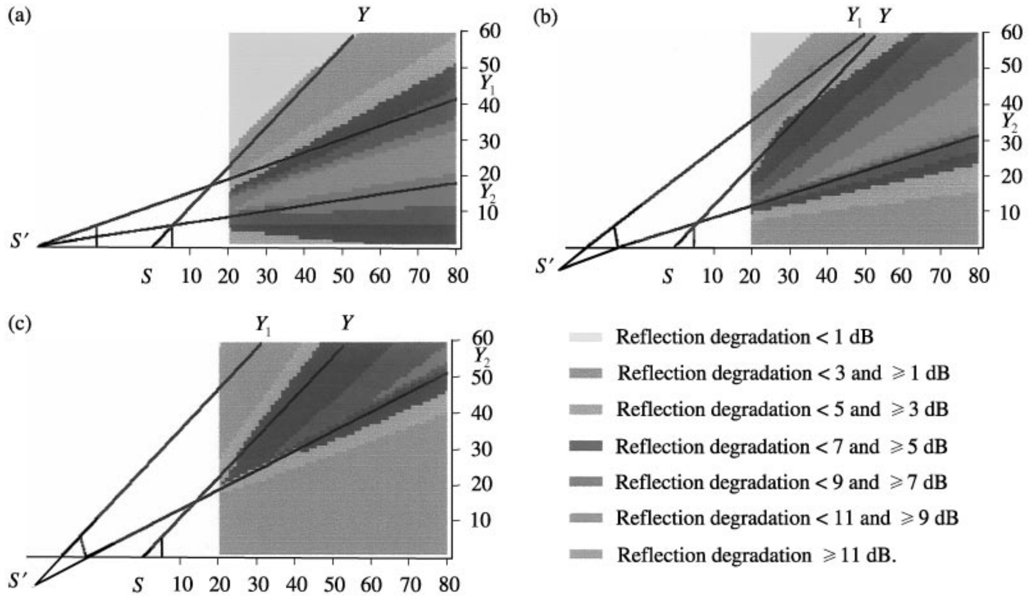

Figure 6. Noise variation behind the first barrier for tilt angle of second barrier: The distance from the source to the nearside barrier = 5 m, frequency for analysis = 500 Hz; The height of nearside barrier = 6 m, height of farside barrier = 6 m; the horizontal distance between the barrier = 20 m; and tilted angle of farside barrier (a) = 0°; (b) = 10°; (c) = 15°.

degradation zone will extend and shift to the high level. The degradation of insertion loss reduces at the lower receiver but increases at the higher receiver.

(3) *Low-frequency effects*. The wavelength of low-frequency sound wave is broad and their reflection characteristic is not similar to that of the optical. Slightly tilting the barrier cannot alter their reflection angle. For low frequency, although the degradation of insertion loss by the second barriers is less, the reflection noise reduction by inclined barrier is also lower.

3. METHODS FOR REMEDYING THE ADVERSE EFFECT BY INCLINED BARRIER

From the above discussion, we found that the degradation of insertion loss at lower receivers can be eliminated when the barriers tilted at 10° or above. It is a good noise control measure for protecting low-rise buildings. However, this approach may not be used in areas where most of the sensitive receivers are high-rise buildings such as Hong Kong. It is because the reflected noise is not absorbed but redirected to a high level and significantly increases the noise levels at higher receivers. From this point of view, methods for remedying the adverse effect by the inclined barrier will be discussed below.

Balcony: it may be provided as a combination design with the inclined barrier. The basic idea of balcony is similar to that of installing a barrier at the building. It allows natural ventilation of buildings while providing some reduction of external noise levels inside buildings. Traffic noise cannot transmit into the building directly.

The efficiency of a balcony for traffic noise protection is dependent on the angle of incidence of the source to the receiver. The level of noise attenuation is directly proportional to the angle of incidence. If the angle of incidence increases, the attenuation also increases.

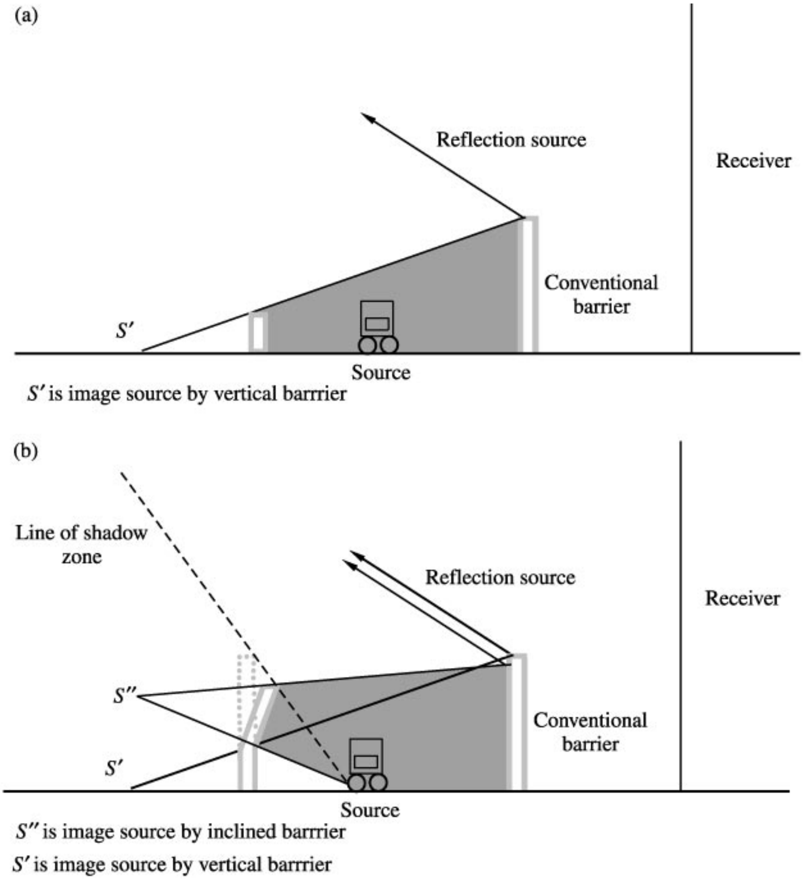

Figure 7(a). Vertical part of composite inclined barrier. (b). Inclined part of composite inclined barrier.

A balcony is particularly useful for receivers on the upper floors and thus can supplement the inclined barrier.

Composite inclined barrier: normally the inclined barrier is angled back from the noise source and attempts to redirect the reflection noise to a high level. However, the barrier can be a composite of vertical and angled forth from the sound source (Figure 7). The lower part of the barrier is placed vertically to minimize the obstruction of traffic road. The height of the vertical lower part of the barrier must be lower than the intersection point of the farside barrier and the shadow line from the image source to the top of nearside barrier (Figure 7(a)). The image source model can be applied to identify the angle of inclination of the upper part. The angle can be rotated so that the illuminated zone from S″ (shaded area) can be shielded by the primary barrier (Figure 7(b)).

The advantage of tilting the upper part of the farside barrier inward to the traffic road is not only minimizing the reflection noise deflected to a high level but also reducing the height of barrier. When the barrier tilted inward to the traffic road, the short line between the sound and the top of barrier becomes shorter. In this case, the excess attenuation is obtained by an inclined barrier, which is higher than a conventional barrier at the equality height. From Figure 7, it can be seen that design using geometrical drawing can be straightforward and no calculation is required.

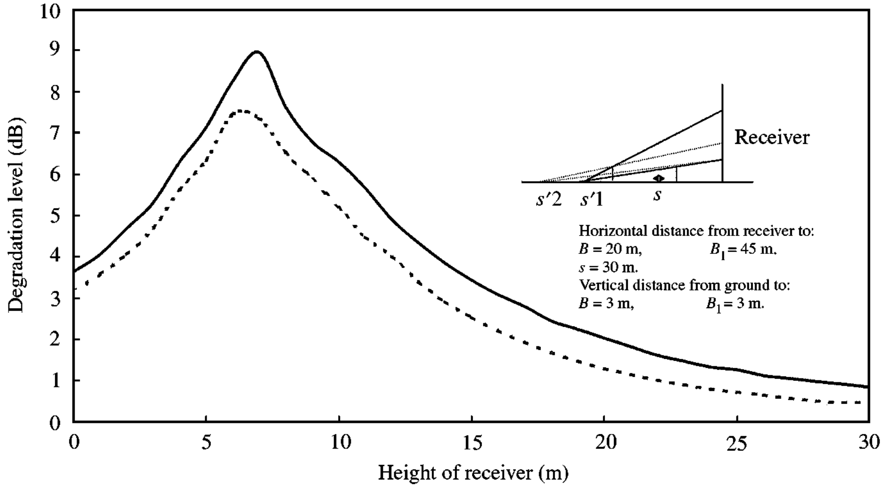

Figure 8. Comparison of degradation level as single- and two-image sources. ——, single image source; – – –, two image sources.

4. IMAGE SOURCE MODEL FOR PRACTICAL APPLICATION

In the above studies, the degradation due to reflection by second barrier is up to 10 dB while the reflection effect is usually around 5 dB in the site measurement. One of the reasons is the size of the source. In this study, the measurement result is undertaken in single line source of the four-lane traffic road. It can help us to more easily identify the worst reflection case and to locate the critical regions of degradation zone on changing the inclined angle of farside barrier. However, in the real case, traffic flow is distributed on every lane, the degradation effect should be counted as the summation of reflection effects at all of the lanes. Also, in practical case, two barriers may not be completely parallel to each other. In such a case, the reflection source cannot be predicted as completely reflected by a single image. The image source will widen and can be estimated as two or more image sources emitted behind the farside barrier. In Figure 8, two image sources have been used to estimate the reflection effect by a single-line source. It can be seen that the degradation level decreases as the number of image source increases, due to the diffusive reflection.

5. CONCLUSION

In this study, the Maekawa diffraction model is applied in prediction of the reflection on the edge of barrier using the concept of virtual barrier. The results of this study show that the average noise level at lower receivers behind the nearside barrier could be reduced by 4, 6 and 10 dB for 125, 250 and 500 Hz, respectively, by tilting the angle of the farside barrier by over 10°. This result seems to be sufficient to counteract the reflected noise problems at lower receivers. It is also noted that degradation is less for low frequency. However, the problem of reflection noise is shifted to a higher receiver. Although reflective noise will slightly decay as the distance increases, the degradation of insertion loss for higher receivers is still higher.

The simple image source and virtual barrier model based on the Maekawa model computer program can help us to locate the critical reflection zone with different tilted angles of the barrier. Based on the image source model, appropriate improvements of the inclined barrier can be designed easily by using geometrical drawings without calculation.

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