Equivalence in diffraction-reducing efficiency between T-profile and thick barrier against road traffic noise

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Abstract: Diffraction-reducing efficiency of a T-profile noise barrier is discussed using boundary element analyses considering a point source against an infinitely long barrier. The efficiency against a fixed point source includes both an increased thickness effect due to the T-profile cap and an interference effect due to phase difference between propagation paths around cranked edges of the cap. The latter interference effect depends on the relationship between wavelength and geometries; the effect disappears for incoherent point sources moving parallel to the barrier. For incoherent line sources such as road traffic noise, the efficiency of the T-profile barrier is almost equivalent to that of a thick barrier, and difference between them is almost less than 1 dB when the T-cap depth is equal to or less than 1 m. As a result, reduction in road traffic noise by a T-profile barrier is approximately calculated using a kind of engineering prediction models based on geometrical acoustics.

Keywords: Noise barrier, Road traffic noise, Diffraction, Boundary element method

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1. INTRODUCTION

Barriers have been applied for a long time to reduce noise around surface transportation such as road traffic and railways [1]. Tall barriers bring large reduction of noise diffraction, and also cause non-acoustic problems, for example, sunshine obstruction and landscape disturbance. In order to obtain large efficiency using lower barrier, May and Osman introduced a T-profile noise barrier (i.e., a vertical barrier capped with a horizontal strip) along an expressway in the end of 1970s [2]. In later years, it is confirmed that the T-profile barrier has larger efficiency to reduce diffraction compared to a simple barrier, by scale-model experiments [3,4], full-scale experiments [5], and numerical simulations using analytical solutions [6–8] or boundary element method (BEM) [9–13].

Noise-shielding efficiency of the T-profile barrier is believed to be a function of the “effective height” [10] which is defined by the intersection of two rays projected from source and receiver to graze two edges of the cap strip on the top of the T-profile barrier. If so, it is expected that the efficiency of the T-profile barrier should be approximated by that of a thick barrier with a thickness equivalent to the depth of the cap strip as shown in Fig. 1. In other words, the T-profile barrier efficiency may be estimated easily by a simple calculation method for a thick barrier (sometimes called as a “wide” barrier) [14]; Maekawa’s empirical chart [1,15] is applied twice for two diffraction paths (for instance, S-X-R and X-Y-R in Fig. 1). Similar methods for a thick barrier are introduced in some engineering methods for propagation prediction such as the ASJ RTN-Model 2008 [16] or the Harmonoise/Imagine model [17]. If the T-profile barrier efficiency is able to be estimated by such a calculation easier than scale-model experiments or numerical analyses, it will enable the T-profile barrier efficiency to be included in making noise maps for environmental impact assessment and planning actions for noise abatement programs.

In the present paper, the hypothesis on the equivalence in efficiency between T-profile and thick barriers shown in Fig. 1 is discussed, to establish an easy method to estimate the T-profile barrier efficiency against road traffic noise.

2. NUMERICAL ANALYSES

In a foregoing work using two-dimensional BEM analyses, it is concluded that the difference between T-profile and thick barriers is less than 0.6 dB [18]. Two-dimensional analyses considering a coherent line source are, however, insufficient to estimate efficiency of barriers with complicated shapes against an incoherent line source.
which approximates noise from vehicles in a road lane [11]. In the following sections, BEM analyses considering a point source and an infinitely long barrier are introduced. As proposed by Duhamel [19], two-dimensional BEM solution for a coherent line source is converted using spatial Fourier transform into three-dimensional solution for a point source. In the present paper, this transformed solution is referred to as “2.5-dimensional BEM.”

2.1. Geometries

Diffracted sound field behind a barrier is calculated using the 2.5-dimensional BEM, considering a geometry shown in Fig. 2. A barrier with height \( H = 5 \) [m] and infinite length stands on \( z \)-axis on the ground. All surfaces of the barrier and ground are reflective. Point sources are located in the range of \(-1000 \leq z_S \leq +1000\) [m] at intervals of 10 m on three traffic lanes \((x_S = -5, -10 \text{ and } -20 \) [m]) parallel to the barrier. A receiver is fixed at \( x = +20 \) [m]. The point sources and the receiver are set on the ground surface to avoid interference due to ground reflection.

2.2. Shapes of Noise Barriers

The efficiencies of the noise barriers shown in Fig. 3 are examined. The Fig. 3 shows cross-sectional profiles; the noise source is assumed to be located on the left-hand side and the receiver is on the opposite side. In this paper, barrier shapes are described by combinations of the following abbreviations: thick (abbreviated to “T”), L-shaped (“L”), J-shaped (“J”), delta (“D”) profiles are considered, with inclined top edge in the source side (“S”), the receiver side (“R”), and in both sides (“B”). Abbreviation “LB” is identical to so-called “T-profile,” and similarly “JB” to Y-profile. The inclined top edge of the barrier is referred to as a “cap” hereafter. Barrier thicknesses or cap depths (defined as \( t \) in Fig. 3) of 0.5 m, 1.0 m and 2.0 m are abbreviated to “05,” “10” and “20,” respectively. For example, an abbreviation “LS05” denotes the L-shaped profile with a cap of a depth of 0.5 meters in the source side.

The height of all barriers is fixed at 5 m, and their surfaces are reflective.

3. EFFICIENCY COMPARISON BETWEEN T-PROFILE AND THICK BARRIERS

3.1. Efficiency against a Single Point Source

With a point source set at \((x_S, z_S) = (-5, 0)\) [m], sound pressure levels (SPLs) at the receiver are calculated using 2.5-dimensional BEM for pure tones at intervals of 1/15 octave. The 2.5-dimensional BEM analysis for each pure tone is based on an integration of a series of two-dimensional BEM solutions at intervals of less than 2 Hz. Figure 4(a) shows the frequency characteristics of the SPL behind barriers LS05 (an L-shaped barrier with a source-side cap of 0.5 m depth), TS05 (a 0.5 m thick barrier), and a simple barrier. SPL is normalized with the power level of the point source. It is shown that all barriers shield sound efficiently in high-frequency range. TS05 reduces diffrac-
tion more than the simple barrier, and the difference between them increases at high frequencies. The periodic pattern in the frequency characteristics for LS05 is due to the cap-induced interference shown in Fig. 4(b) [20,21]. SPL rapidly decreases at frequencies where the path difference between the direct and reflected paths to the cap corresponds to odd-numbered multiples of the half-wavelength. The interference frequencies, $f_n$, are shown in the frequency characteristics.

Results for LR05 (receiver-side cap of 0.5 m depth), LB05 (0.5 m caps on both sides, i.e., T-profile), and LS10 (source-side cap of 1.0 m depth) are shown in Fig. 5. $f_0', f_0$, and $f_0''$ in the figures (a) and (b) denote the interference frequencies calculated by applying the hypothesis (Fig. 4(b)) to the receiver-side cap. The cap-induced interference hypothesis is still reasonable, and the frequency characteristics of LB05 are the superposition of the interference SPL dips for LS05 (Fig. 4(a)) and LR05.

Now let the barrier shape reset to LS05. Figure 6 shows results for other source positions $(x_S, z_S) = (-10, 0)$ and $(-20, 0)$ [m]. When the point source moves away from the barrier compared to the position $(-5, 0)$ in Fig. 4(a), the path difference beneath the cap (Fig. 4(b)) increases and the interference frequencies shift to lower frequency range. Also, the SPL dips due to the interference are shallow for far source positions. Figure 7 shows results for the source positions $(x_S, z_S) = (-5, 40)$ and $(-5, 80)$ [m] where the source moves parallel to the barrier from the position $(-5, 0)$ in Fig. 4(a). When the point source moves along a certain traffic lane, the SPL dips shift to higher frequency range for those source positions, because increase in $z_S$ makes decrease in the path difference below the cap.
In Figs. 4 to 7, SPLs for the barriers of types TS/TR/TB are always smaller than that for the simple barrier. The effect of the barrier thickness, that is, difference between the simple and TS/TR/TB, increases with increasing frequency. The SPL curves for TS/TR/TB barriers appear as envelopes over SPL peaks of the frequency characteristics with interference dips for LS/LR/LB barriers. It is interpreted that efficiencies of L-profile or T-profile barriers consist of the thickness effect and the cap-induced interference effect.

SPLs for five frequencies at intervals of 1/15 octave are summed incoherently to approximate 1/3-octave band SPLs relative to the source power levels. A-weighted sound power spectrum of the point source is set in 1/3-octave band levels, assuming vehicle noise defined in ASJ RTN-Model 2008 [16] (light vehicles, steady traffic flow, 80 km/h, dense asphalt pavement). The power spectrum is combined with the propagation characteristics calculated above, to obtain A-weighted SPL at the receiver, \( L_{pA} \) [dB]. Absorption by the atmosphere [22] is also considered for the diffraction path length as propagation distance, assuming homogeneous atmosphere at a temperature of 15 degrees C, a relative humidity of 60%, and an atmospheric pressure of 101.325 kPa. Neither turbulence of atmosphere nor refraction due to spatial variation of sound speed is considered.

Figure 8 shows \( L_{pA} \) as a function of source position \( z_S \) for a range of \( -1,000 \leq z_S \leq +1,000 \) [m] to obtain A-weighted sound exposure levels. Then the equivalent continuous A-weighted sound pressure level \( L_{Aeq,1h} \) [dB] is calculated considering a traffic flow volume of 1,000 vehicles per hour. 1/3-octave band levels from 50 Hz to 5 kHz are calculated in these procedures.

Figure 9 shows frequency characteristics of \( L_{Aeq,1h} \) for barriers with thickness or crank depth of 0.5 m. Difference due to the lane position \( x_S \) is not so obvious; it means contributions from nearest and farthest lanes are almost equivalent behind a barrier along road traffic. Curves for barriers are categorized into two groups: the first group monotonically with increasing \( z_S \), the curve for LS05 rises and falls in complicated patterns [12]. The \( L_{pA} \) curve for LS05 is less than that for TS05 significantly in a certain range of \( z_S \) because of the cap-induced interference (Figs. 4 and 7), and approaches asymptotically to TS05 or Simple for large \( z_S \). Over-all (OA) \( L_{pA} \) curves for all three barriers in Fig. 8(c) decreases monotonically with increasing \( z_S \). The thickness effect (i.e., difference between Simple and TS05) is almost constant for any \( z_S \). In contrast, the effect of cap-induced interference (i.e., difference between TS05 and LS05) vanishes for \( z_S \) farther than 250 m.

3.2. Efficiency against an Incoherent Line Source

A series of \( L_{pA} \) values shown in Fig. 8 for discretized source positions are integrated incoherently for the range of \(-1,000 \leq z_S \leq +1,000 \) [m] to obtain A-weighted sound exposure levels. Then the equivalent continuous A-weighted sound pressure level \( L_{Aeq,1h} \) [dB] is calculated considering a traffic flow volume of 1,000 vehicles per hour. 1/3-octave band levels from 50 Hz to 5 kHz are calculated in these procedures.

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includes Simple and JS05, and the other group includes TS05, LS05 and DS05. Now $\Delta L_{Aeq}$ [dB] for each barrier is defined as difference in the $L_{Aeq,1h}$ relative to the Simple barrier. Figure 10 shows $\Delta L_{Aeq}$ [dB] for barriers considered in Fig. 9. Periodic and steep dips shown in Figs. 4 to 7 due to cap-induced interference now disappear in Fig. 10, because the dips are averaged out by integrating contributions from point sources in line on a traffic lane [11]. $\Delta L_{Aeq}$ for J-shaped barrier JS05 is almost zero. $\Delta L_{Aeq}$ for thick barrier TS05 (i.e., the thickness effect) increases with increasing frequency. Delta-shaped DS05 and L-shaped LS05 have almost equivalent $\Delta L_{Aeq}$, and slightly efficient compared to the thick barrier TS05. Similarly to the tendency in Fig. 6, difference between LS05 and TS05 decreases for traffic lanes in farther positions.

Figure 11 shows difference in $\Delta L_{Aeq}$ due to cap direction. Similar to the tendency shown in Fig. 5, effect of interference induced by receiver-side cap is smaller than that induced by source-side cap (Fig. 10(a)). It is because the source is closer to the barrier than the receiver in this case; as shown in Fig. 6, the interference effect increases when the source/receiver (whichever the cranked top faces to) is set closer to the barrier. Now JR05 is as effective as TR05 while JS05 was ineffective in Fig. 10(a). The reason of the difference is depicted in Fig. 12; JR05 makes almost double-diffraction situation for the traffic lane at $x_S = -5$ [m], while JS05 makes single-diffraction situation for the receiver because the path is off the lower edge. JR05 is, however, ineffective for lanes at $x_S = -10$ [m] or $-20$ [m] ($\Delta L_{Aeq}$ graphs omitted) because the path comes off the lower edge and double diffraction no longer occurs. In
Fig. 11(b), superposition of interference effects due to those source-side and receiver-side cranks is equivalent to the effect of both-side crank. JB05 is significantly efficient compared to JS05 or JR05 because of double diffraction and interference inside an upper cavity between two inclined edges.

Figure 13 shows relationship between $C_1$ and $L_{Aeq}$ and depth of the cap. When the cap depth increases compared to 0.5 m depth (Fig. 10(a)), the thickness effect increases significantly while the cap-induced interference effect increases slightly.

### 4. ERROR DUE TO SIMPLIFICATION IN EFFICIENCY ESTIMATION OF T-PROFILE BARRIER

In the previous section, it is concluded that the cap effect of T-profile barrier consists of thickness effect and cap-induced interference effect. Let us discuss a simple and easy method to estimate T-profile barrier efficiency; as shown in Fig. 1, the T-profile barrier is approximated to a thick barrier with an equivalent thickness. This approximation implies that the thickness effect is included but the crank-induced interference effect is excluded in the efficiency estimation. The thickness effect is easily estimated by applying Maekawa’s empirical chart [1,15] twice for S-X-R and X-Y-R in Fig. 1 [14]. In this section, error due to neglecting the cap-induced interference effect in the efficiency estimation is investigated.

Differences in over-all $L_{Aeq,1h}$ (i.e., $\Delta L_{Aeq}$ values over abscissa labels “OA” in Figs. 10, 11 and 13) for thick barriers and barriers with an L-shaped cap are summarized in Table 1(a). For example, the difference between TS05 and LS05 is shown in a column “TS–LS.” Underlined column labels indicate that the total depth of barrier caps (i.e., equivalent thickness) is equal to or less than 1.0 m. Values in the table are identical to the error due to neglecting the cap-induced interference in the simplified estimation of capped barrier efficiency. Similarly Table 1(b) is shown for difference between thick barriers and barriers with a delta-shaped cap. All values in the tables are positive; it means that $L_{Aeq,1h}$ is always overestimated because of the simplification by neglecting the crank-induced interference. The error for caps sticking out to both source- and receiver-sides (i.e., values in columns groups “TB–LB” or “TB–DB”) are generally larger than that for single-side caps. Regarding a T-profile barrier capped with 1.0 meter width strip (LB05), the simplification error is around 1 dB. When total depth of the cap is equal to or less than 1.0 meter (i.e., columns with underlined labels), the simplification error is generally less than 1 dB.

In all calculations above, sound power spectrum of noise from vehicles running on dense asphalt pavement is considered. When the pavement condition is changed to JR05, the traffic lane is at $x_S = -5$ [m].

![Fig. 12 Cross-sectional view of propagation paths around JR05 and JS05 barriers.](image)

![Fig. 13 Change in $L_{Aeq}$ compared with the simple barrier: effect of cranked-top depth. The traffic lane is at $x_S = -5$ [m].](image)

![Table 1 Over-all $\Delta L_{Aeq}$ [dB], defined as differences in over-all $L_{Aeq,1h}$ for thick barriers and other barriers.](table)

| $x_S$ [m] | TS–LS | TR–LR | TB–LB |
|---|---|---|---|
| -5 | 0.8 1.1 1.6 | 0.5 0.5 0.4 | 1.3 1.6 2.3 |
| -10 | 0.7 0.8 1.0 | 0.5 0.5 0.4 | 1.1 1.2 1.5 |
| -20 | 0.5 0.4 0.3 | 0.5 0.4 0.3 | 0.9 0.8 0.7 |

(b) Barrier with Delta-shaped cap

| $x_S$ [m] | TS–DS | TR–DR | TB–DB |
|---|---|---|---|
| -5 | 0.7 1.0 1.3 | 0.5 0.4 0.3 | 1.1 1.4 1.6 |
| -10 | 0.6 0.7 0.7 | 0.6 0.4 0.3 | 1.0 1.1 0.9 |
| -20 | 0.5 0.5 0.4 | 0.5 0.4 0.3 | 0.8 0.7 0.5 |
porous (drainage) asphalt, dominant frequency components would shift to lower-frequency range compared to Fig. 9, then the over-all $\Delta L_{Aeq}$ would be smaller than values in Table 1.

5. CONCLUSIONS

Noise-shielding efficiency of T-profile barriers against road traffic noise has been investigated by 2.5-dimensional numerical analyses. It has been concluded that the efficiency improvement due to the top cap consists of the thickness effect and cap-induced interference effect. Although the cap-induced interference is large enough to be considered in the barrier design for a single fixed point source, it is no longer so effective when averaged for incoherent multiple sources moving parallel to the barrier. The cap-induced interference effect is generally less than 1 dB in $L_{Aeq}$ behind the barrier when the cap depth (an equivalent thickness) is equal to or less than one meter.

Recently acoustical devices with absorbers and/or resonators are often mounted on the top edge of noise barrier. It has been confirmed that these edge-modifying devices reduce diffraction behind the barrier [18,23–25]. Authors have proposed a series of procedures to include acoustical efficiency of these devices on barrier edge in engineering models for prediction of outdoor sound propagation [16,20,26,27]: firstly the diffraction-reducing efficiency of those devices is measured as SPL reduction relative to a thick barrier with a thickness equivalent to the device size, and then the measured efficiency is substituted as an additional effect relative to an equivalent thick barrier. Outer shapes are approximated to equivalent thick barrier in the proposed methods, although the outer shapes of those edge devices may cause the cap-induced interference discussed in the present paper. It is expected, on the basis of values in Table 1, that this approximation would cause overestimation less than 1 dB in $L_{Aeq}$ behind the edge-modified barriers, when the equivalent thickness of the edge device is equal to or less than one meter.

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