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Impact and Control of Reflected Noise from an Overpass Bottom

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Abstract: This study examines the effects of noise reflected from the overpass bottom under various conditions using onsite measurements and model simulation. Reflected noise from the overpass bottom may be as high as 8 dB(A). Bottom materials (steel and reinforced concrete (RC)) have no discernible effect on the reflected noise level. As the height of an overpass increases, the level of reflected noise decreases. When an overpass is parallel to the noise source (i.e., the freeway), the size of the area impacted by reflected noise increases. As the sound absorption rating of the material installed at the overpass bottom increased, the level of reflected noise decreased. A sound absorbing material with a sound absorption rate of at least 0.60 is recommended to reduce reflected noise level. When the distance between the overpass side and a receiver exceeded 30 m, the level of reflected noise level reduced significantly. Therefore, if the distance between a residential area and overpass could be increased to create a buffer zone coupled with the installation of sound absorbing material at the overpass bottom, the impact of reflected noise on nearby residents can be reduced.

Keywords: overpass; reflected noise; bottom material; model simulation; sound absorbing material; buffer zone

1. Introduction

In the recent years, many efforts have been spent by the scientific community to study and propose new mitigation systems for the main sources of noise: Road traffic [1,2], railway traffic [3,4], airport [5,6], and wind turbines [7,8]. Unfortunately, noise pollution continues to be a major health problem around the world, with millions of people exposed to noise levels leading to health effects studied with sufficient evidence: Sleep disorders with awakenings [9], learning impairment [10–12], hypertension ischemic heart disease [13–15], and noise annoyance [16].

The traffic noise is an environmental problem that typically accompanies urbanization. As the network of roads has expanded, traffic noise has become increasingly annoying to the public. Even if is not the most annoying type of noise, road traffic noise is the most widespread, especially in urban areas, indeed it is considered as a reference in limits assessment [17]. The generation of road traffic noise mainly attributes to the interaction between the tire and the road when vehicles are operated at medium/high speeds. The tyre/road noise is considered to be proportional to the vehicle speed [18]. Noise barriers (NBs), indeed, are the most commonly used approach to mitigate noise and not even the best in a correct action plan phase [19,20]. The use of pavements with low acoustical emission profiles is one of the most applied alternatives to mitigate noise levels [21,22]. Additionally, the fabrication of sound absorption materials is also an important approach to reduce noise. Sound absorption materials decrease noise by disseminating energy and turning it into heat [23]. Porous materials such as absorption foams and fibers are commonly used to reduce noise [24]. The best solutions to be chosen are those mitigating the wider number of citizens, which for road noise can be changing flux, reducing heavy vehicles or changing pavements towards ecological and recycled rubberized asphalts [25].

Reflected noise may occur when acoustic barriers exist on either side of a road, when buildings line the roadside, or when vehicles move through a culvert, an underground passage, or on a double-decker road [26–28]. Generally, reflected noise is most evident within a road when acoustic barriers exist on either side of a road [29]. Other than road width and the material used in the design of acoustic barriers, the noise reflected by acoustic barriers is also affected by natural conditions such as wind speed and wind direction. The volume of reflected noise increases when the distance between roadside acoustic barriers and a vehicle decreases, primarily because when a vehicle is close to acoustic barriers, the area on acoustic barriers available for sound reflection increases [30,31]. Buildings on either side of a road are also an important source of reflected noise. When building facades have large, flat, and smooth surfaces, the noise from vehicles is reflected easily, increasing the noise level at and around roadsides [32]. Urban geometry also plays an important role in traffic noise reflection and propagation. Silva et al. [28] evaluated the relationship between traffic noise and urban geometry using the sky view factor (the degree of sky obstructed by buildings). The authors indicated that the noise level was higher in areas with low sky view factor (greater sky obstruction caused by the buildings) because of higher noise reflection and propagation. Traffic noise levels may change at different heights of receivers. Mak et al. [33] evaluated vertical distribution of traffic noise levels at different floor levels of a 20-storey residential building in Hong Kong using measurement and the Calculation of Road Traffic Noise (CRTN) model prediction. The results showed that traffic noise level decreased with increasing floor level.

Recently, densely populated urban areas have been the target for overpass construction in Taiwan. When an overpass project is complete, the old road remains in use under the overpass. When traffic noise from vehicles on the road under the overpass hits the bottom of the overpass, sound is reflected. Figure 1 shows the formation of reflected noise from the bottom of the overpass. In Taiwan, it is normal to have residential buildings on both sides of the elevated road in urban areas. Therefore, it is common to encounter noise barriers at roadside measurement sites. Although acoustic barriers on either side of the old road were installed to block traffic flow noise, the acoustic barriers are usually not high enough to reach the bottom of the overpass. Therefore, direct noise is conveyed from the gap in the top of the acoustic barriers to the bottom of the overpass, generating reflected noise. The reflected noise then propagates to the residential area on both sides of the road, increasing the overall noise level. As the literature shows, reflected noise increases overall noise levels. Therefore, the effects of reflected noise on overall noise levels and the effects of feasible improvement measures for controlling reflected noise must be assessed. Herman et al. [26], who explored the impact of reflected noise produced in the culvert on I-675 passing underneath Alexanderville-Bellbrook road in Dayton, Ohio, showed that reflected sound was the main cause of increased noise around the highway culvert. Reflected noise typically increases noise levels by at least 5 dB(A). A study by the Washington State Department of Transportation (WSDOT) found that noise around a double-decker road was mostly reflected noise caused by noise from the lower deck of the high-rise expressway hitting the bottom of the upper deck. Simulation results using the Highway Traffic Noise Model (TNM) v. 2.5 (Federal Highway Administration (FHWA), USA) showed that the noise increase caused by reflected noise could be as high as 11 dB(A) [34]. To date, although reflection of traffic noise caused by noise barriers [31,35,36] and building facades and structures [28,37,38] has been well studied, information regarding noise reflected by the bottom of overpasses is still limited. Through onsite measurements and model simulation, this study explored the effect of noises reflected by the bottom of overpasses under different conditions (different bottom materials, different overpass heights, and different road structures (the overpass is perpendicular or parallel to the source road)). This study also simulated the noise reduction performance of the sound absorbing material installed at the overpass bottom. Assessment results will determine the contribution of reflected noise to overall noise and the efficacy of sound absorbing materials for the abatement of noise levels. The obtained information will be helpful in controlling existed reflected noise near overpasses. The results will also provide useful information to urban design in the future.

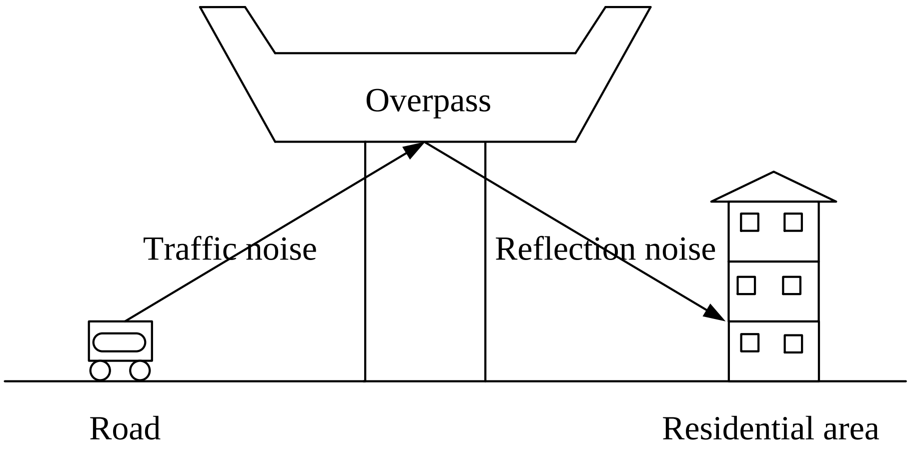

Figure 1. Formation of noise reflected from the overpass bottom.

2. Materials and Methods

2.1. Measurement Methods and Investigation Sites

A Class 1 sound meter (NL-32; Rion Co., Ltd., Tokyo, Japan), which complies with International Electrotechnical Commission (IEC) 61672-1, was used. The measurements were acquired using the reflected noise measurement plan recommended by the WSDOT [34] and the Ohio Department of Transportation [23]. Measurements were conducted in accordance with the method approved by the FHWA [39] and American National Standards Institute (ANSI) S12.8 Standard [40]. Each measurement at each measurement point was taken over a period of 1 hour to obtain a representative traffic noise equivalent sound level (L_{Aeq}). When conducting measurements, the sound meter was in the A frequency-weighting mode and fast time-weighting was adopted.

Three field investigation sites with reflected noise were selected. The road sections chosen at each site were roughly 200 m long. Suitable measurement locations were established to identify the noise profiles in the area. To determine the noise profiles at different heights, measurement points were at heights of 1.5 and 4.5 m. Two locations were selected at each site. Noise levels were measured at heights of 1.5 m and 4.5 m at each location. Monitoring at the 4 measuring points was conducted simultaneously. To characterize decreases in reflected noise as distance from the noise source of reflected noise increases, cases from Ohio [26] and ANSI [40] methods were used to establish measurement locations at different distances from the source of reflected noise. Since American design regulations are mostly adopted for road design in Taiwan, the deployment planning of this study was conducted making reference to the I-5 Ship Canal Bridge Study of Washington State Department of Transportation [34] and the Measurement of Highway-related Noise of the Federal Highway Administration (FHWA) [39]. The I-5 Ship Canal Bridge Study set up 11 measuring points on both sides of the road within a distance of 1 km to measure the noise level during peak traffic hours. The distance between measuring points was mostly around 200 to 250 m. The area was divided into 4 divisions (NE, SE, NW, and SW) in order to facilitate simulation with the model [34]. If sensitive points at different heights need to be considered, apart from the basic height (1.5 m), measuring points may also be set at the height of 4.5 m and 7.5 m. If noise attenuation needs to be considered, measuring points may be deployed at the distance of 7.5, 15, and 30 m from the centerline of the nearest lane [39].

2.2. Different Overpass Bottom Materials

Investigation Site A was located on the side of National Freeway No. 1 (New Taipei City, Taiwan). An overpass is parallel to this section of the freeway. Overpass height is roughly 13 m. Acoustic barriers on either side of the freeway were installed to block traffic flow noise. However, since the acoustic barriers are not high enough to reach the bottom of the overpass, direct noise is conveyed from the gap in the top of the acoustic barriers to the bottom of the overpass, generating reflected noise. This increased noise level in the nearby residential area adversely affects the quality of life for residents in nearby areas. Conditions at Site A were as follows. This section is the point where steel and RC overpass bottom materials connect. The height of the steel and RC overpass sections are the same. The overpass is parallel to the freeway, the noise source. The materials on the bottom of the overpass vary, and the noise level generated by traffic on the freeway is stable. Two measurement locations, the (1) steel section and the (2) RC section of the overpass, were selected to measure the noise levels at heights of 1.5 m and 4.5 m at each point. Consequently, four measurement points existed. The two measurement locations were around approximately 100 m apart and around 5 m from the side of the overpass. Figure 2 shows site conditions and the layout of investigation Site A.

(**a**)

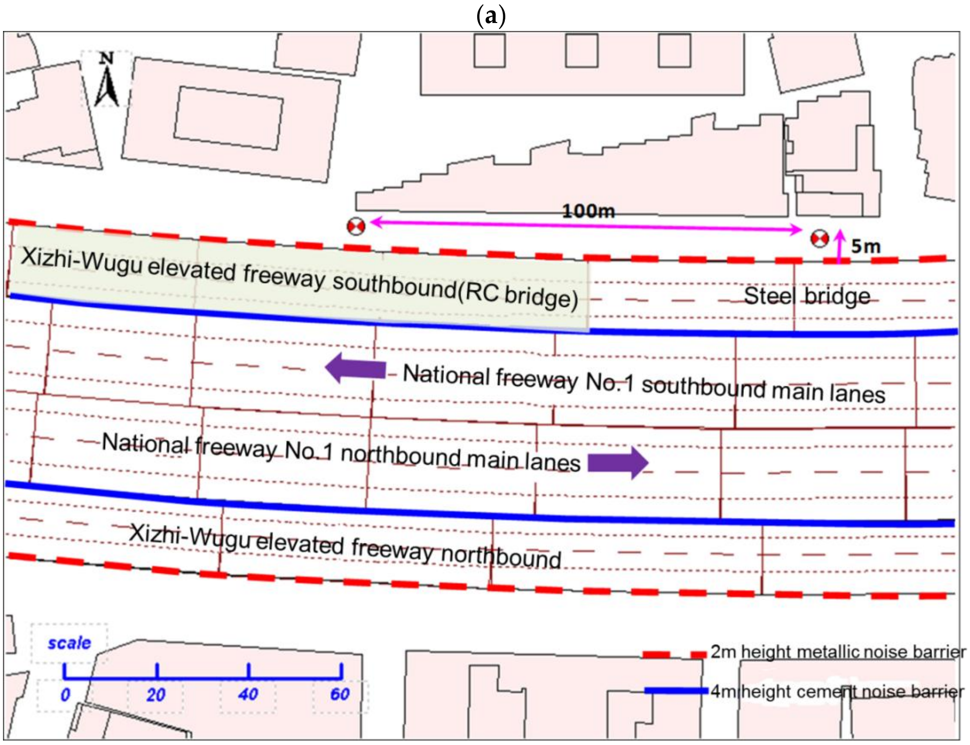

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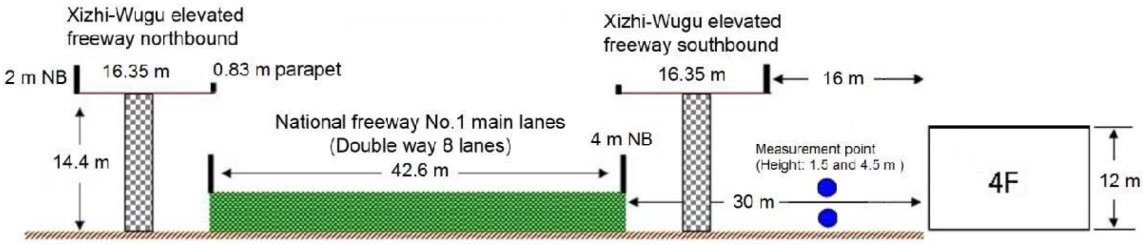
Figure 2. *Cont.*



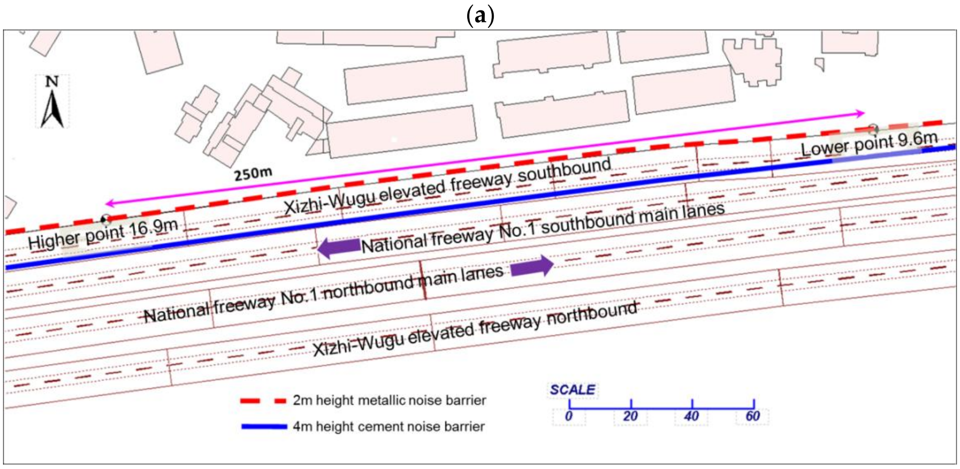
(**c**)

Figure 2. Site conditions and layout of Site A (**a**) The different material of bridge deck (bottom: Steel box type girder and concrete I-type beam, respectively; underneath road: 4 m height concrete noise barrier; (**b**) plane view; and (**c**) cross section profile.

2.3. Different Overpass Heights

Investigation Site B was located at the side of National Freeway No. 1 (Taipei City, Taiwan). Similar to Site A, acoustic barriers are not high enough to reach the bottom of the overpass, such that direct noise is conveyed through the gap and hits the bottom of the overpass, generating reflected noise. Conditions at Site B were as follows. The overpass was constructed with RC; the overpass is parallel to the freeway, the noise source; the overpass is around 17 m and 10 m high; and the level of noise generated by freeway traffic is stable. Two measurement locations were set up at the 17 m high section and 10 m high section of the overpass at heights of 1.5 m and 4.5 m. Thus, four measurement points existed. The two measurement locations were around 250 m apart and around 5 m from the side of the overpass. Figure 3 shows site conditions and its layout.

(**a**)



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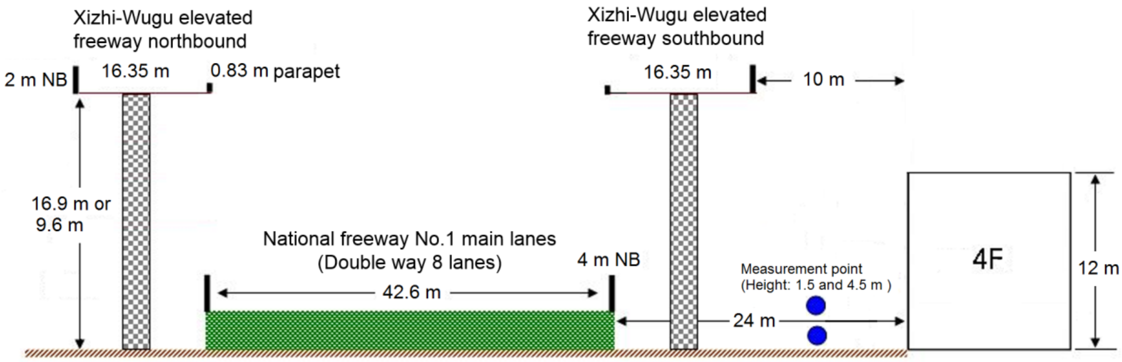

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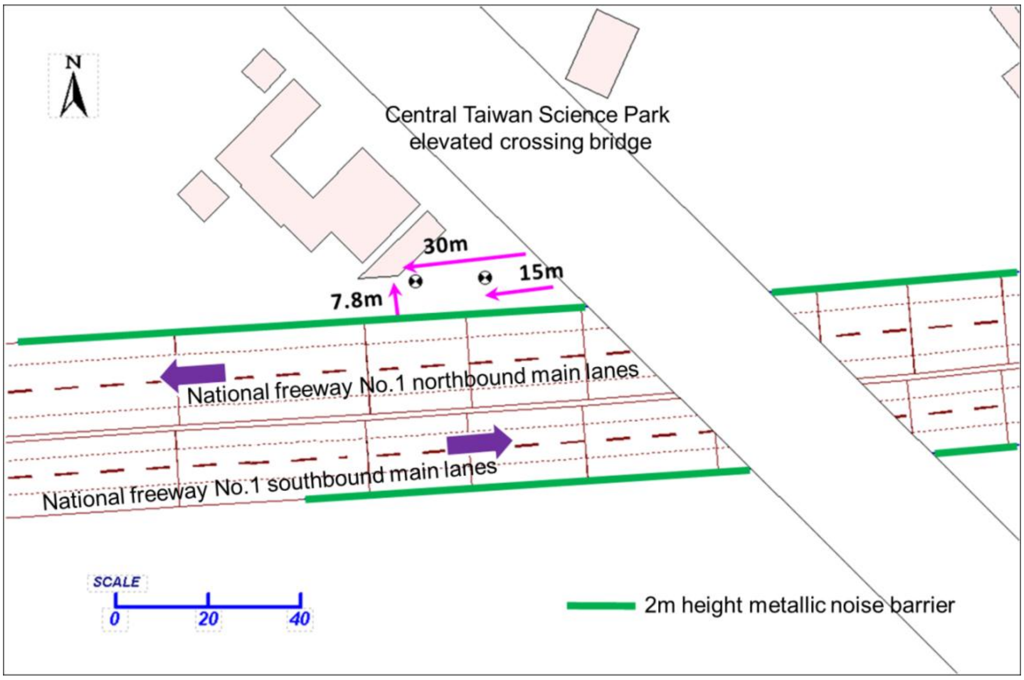
Figure 3. Site conditions and layout of Site B. (**a**) The different height of bridge deck (bottom: Concrete box type girder; underneath road: 4 m height concrete noise barrier); (**b**) plane view; and (**c**) cross section profile.

2.4. Different Road Structures (Overpass Going across the Noise Source Road)

Investigation Site C was located on the side of National Freeway No. 1 (Taichung City, Taiwan). The overpass across this section of freeway is approximately 11 m high. The bottom of the overpass is RC. As with sites A and B, the acoustic barriers are not high enough to reach the bottom of the overpass. The direct noise passes through the gap and hits the bottom of the overpass, generating reflected noise. Site C and sites A and B differed in their geometric relationship between the overpass and the freeway. Two measurement sites were set up at (1) 15 m and (2) 30 m from the side of the overpass with measurement points at heights of 1.5 m and 4.5 m, respectively, for a total of four measurement points. The two measurement locations were around 8 m from the side of the freeway. This site was used to explore variations in reflected noise at different distances from the overpass. Figure 4 lists site conditions and its layout.

(**a**)

Figure 4. *Cont.*



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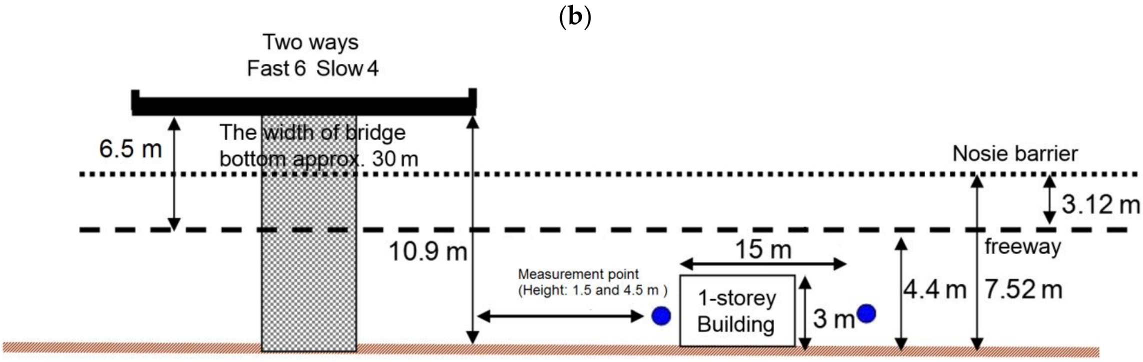

(**c**)

Figure 4. Site conditions and layout of Site C. (**a**) The different structure of road (the elevated road intersects with the bottom noise emission road); (**b**) plane view; and (**c**) cross section profile.

2.5. Sound Field Simulation

In this study, Cadna A v. 4.3.144 (DataKustik, Germany) was applied for sound field simulation and analysis via a 3D sound field model. The German RLS-90 traffic noise model adopted in Cadna A noise prediction and assessment software is an approved noise prediction model by the Technical Regulation for Road Traffic Noise Assessment Models promulgated by Taiwan Environmental Protection Administration (EPA). In RLS-90 traffic noise model, the Emission Level ($L_{m,e}$) at the position 25 m horizontally from the centerline of the outer lane and 4 m vertically from the road surface was calculated with traffic flow (M) and heavy vehicle ratio (P) and modified with maximum allowable speed correct value (D_v), pavement type correct value (D_{Stro}), road longitudinal slope correct value (D_{Stg}), and reflection on particular conditions correct value (D_E):

$$L_{m,e} = L_m^{(25)} + D_v + D_{Stro} + D_{Stg} + D_E$$

where the boundary conditions of $L_m^{(25)}$ are described as follows:

1. Twenty five meters horizontally from the centerline of the outer lane and 2.25 m vertically from the road surface;

2. The road was paved with non-corrugated mastic asphalt;
3. The maximum allowable speed is 100 km/h;
4. The road longitudinal slope is less than 5%;
5. The free sound propagation on a flat and straight road is a straight line.

The calculation formula is as follows:

$$L_m^{(25)} = 37.3 + 10 \times \log[M \times (1 + 0.082 \times P)]$$

where M is the average hour traffic flow (vs/h).

P is heavy vehicle ratio (vehicles with a net weight of 2.8 tons and above) (%).

The average traffic noise level on the straight lane (L_m) was calculated with considerations of the following factors: Emission Level ($L_{m,e}$), amount of change due to distance and air absorption ($D_{s\perp}$), amount of change due to road surface and whether reduction (D_{BM}), and amount of change due to terrain and construction measures (D_B):

$$L_m = L_{m,e} + D_{s\perp} + D_{BM} + D_B$$

Input parameters for the software include: Terrain, ground level, road width, road elevation, number of lanes, average vehicle speed, traffic flow (light and heavy vehicles), road pavement type, obstacles (noise barriers and buildings), and bridge bottom reflection.

This study included parameters of the surrounding terrain features of each site into 3D sound field modelling. The purpose of sound field model calibration was to make sure that the simulated results derived from this model were close to the actual situations (according to Taiwan's regulations, the difference between the simulated value and measured value should be less than ±3 dB(A). Therefore, related traffic parameters were entered into RLS-90 road noise prediction model to simulate the noise level at various measurement sites. When the simulated noise levels produced by the software were close to the actual noise levels, it meant that the simulated results were credible. After taking into consideration of the parameters on the shape of the elevated road and sound path, as well as proving the credibility of the noise model after on-site measurement data verification, the noise model can serve as a reference for determining the influence level of reflected noise on nearby residence and planning and designing of absorbing material setups for the overpass bottom.

3. Results and Discussion

3.1. Reflection Noise Analysis and Improvement Results with Different Overpass Bottom Materials (Steel and RC)

Table 1 shows simulated values and measurement values with different overpass bottom materials. Table S1 shows Cadna A calibration input parameters at Site A. When subtracting measurement values from simulation values (L_{Aeq},1h), the values at four measurement points differed by 0.5–1.9 dB(A). Since deviations at all four measurement points were ±3 dB(A), the sound field model can be used for simulation assessments at Site A. The noise sources at Site A were mainly northbound and southbound traffic flow on National Freeway No. 1, with traffic volumes of 3903 and 4605 vehicles/hour, respectively. The noise level was around 80 dB, which was sufficiently high to interfere with conversation and decrease work efficiency. Thus, the nearby residential area was adversely impacted by the noise. The noise level at the steel overpass section was slightly higher than that at the RC overpass section, suggesting that the effect of overpass bottom materials on the overall noise level was insignificant. Conversely, at the same measurement location, the measurement values and simulation values (L_{Aeq},1h) were higher when the sound meter was 4.5 m above the ground (roughly sound receiving point on the second floor (2F)) than those when it was 1.5 m above the ground (roughly sound receiving point on the first floor (1F)), indicating that the overall noise level tended to typically increased as the number of floors increased due to the different noise sources at different floors, including reflected noise, diffracted noise (occurred on top of acoustic barriers) and direct noise. Typically, higher floors received more noise from the noise sources mentioned above. Further, as demonstrated by simulation results, traffic noise (direct noise) from the freeway hit the bottom of the overpass, and reflected noise was generated, evidently increasing the noise level in the residential area along the overpass parallel to the freeway. In other words, when the overpass was parallel to the freeway, reflected noise was largely "area-based" with a large impact area.

Table 1. Simulation values and measurement values with different materials on the bottom of the overpass (steel and reinforced concrete (RC)).

Sound Receiving Point	L_{Aeq},1h Simulation Value (1) dB(A)	L_{Aeq},1h Measurement Value (2) dB(A)	Deviation (1)–(2) dB(A)
Steel overpass (sound meter 1.5 m above the ground)	78.7	78.2	0.5
Steel overpass (sound meter 4.5 m above the ground)	81.0	79.1	1.9
RC overpass (sound meter 1.5 m above the ground)	78.6	77.9	0.7
RC overpass (sound meter 4.5 m above the ground)	80.9	79.5	1.4

To identify the effect of reflected noise on the overall noise level and assess the success of noise mitigation by sound absorbing material on the bottom of the overpass, the noise level on different floors of nearby buildings was assessed with Cadna A. Table 2 and Figure 5 list simulation results. The increase in the noise level at different floors due to reflected noise was 1.0–7.8 dB(A) (Table 2). Simulation results also show that reflected noise increased the noise level on low floors more than on high floors. Herman et al. [26] showed that reflected noise was the main cause of increased noise around a highway culvert, and can increase the noise level by ≥5 dB(A). In addition, the WSDOT [34] showed that reflected noise from a double-decker road may be as high as 11 dB(A). Ogata et al. [41] assessed the effect of an overpass built across a railway track on the increase in noise level. The results showed that reflected noise from the bottom of the overpass contributed up to 10 dB increase in wayside noise level. Therefore, our findings are in agreement with the results of other studies. Moreover, since the sound absorption rates of steel and RC overpass bottoms were very close (0 for steel and 0.02 for the RC), the levels of noise reflected by these overpass bottoms were similar. Therefore, the effect of these two materials on reflected noise was insignificant.

Table 2. Simulation results of overall noise level and reflected noise caused by the overpass with different bottom materials.

		Steel Overpass		RC Overpass	
	Floor	L_{Aeq},1h dB(A)	Reflected Noise dB(A)	L_{Aeq},1h dB(A)	Reflected Noise dB(A)
Noise level on each floor	1F	78.2	7.7	78.2	7.8
	2F	80.9	6.9	80.8	6.9
	3F	82.7	4.3	83.1	4.8
	4F	84.8	3.5	84.6	3.6
	5F	84.5	1.1	84.1	1.0

Figure 5 shows simulation results for reflected noise mitigation when the overpass bottom was equipped with different sound absorbing materials. When the sound absorbing material had a sound absorption rate of 0.36, reflected noise on 1F–5F decreased by 0.3–1.5 dB(A). When the sound absorbing material had a sound absorption rate of 0.6 and 0.85, reflected noise on 1F–5F decreased by 0.6–3.0

and 0.8–5.3 dB(A), respectively. Study results show that as the sound absorption rate of the sound absorbing material increased, noise reduction improved. Since human ears can perceive a more than 3 dB(A) change in sound level [34,42], a sound absorbing material with a sound absorption rate of at least 0.60 is recommended to reduce reflected noise level. The WSDOT [27] indicated that on a double-decker highway, when the bottom of the upper decker had a sound absorbing material, noise from the lower decker was absorbed, reducing reflected noise by around 0–4 dB(A). Therefore, these sound absorbing materials can effectively reduce the level of reflected noise.

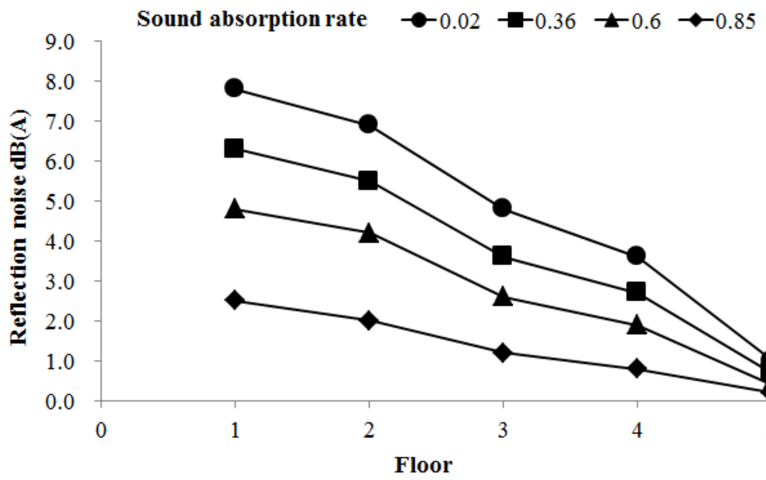

Figure 5. Simulation results for reduction in reflected noise by different materials on the bottom of the overpass (Site A).

3.2. Reflected Noise Analysis and Improvement Results with Different Overpass Heights

Table 3 shows simulation values and measurement values for different overpass heights. Table S2 shows Cadna A calibration input parameters for Site B. When subtracting measurement values from simulation values (L_{Aeq},1h), the deviation values at the four measurement points were −2.7–1.8 dB(A). Since all deviations were less than ±3 dB(A), the sound field model can be used for simulation at Site B. At Site B, the noise sources were mainly northbound and southbound traffic on National Freeway No. 1, with traffic volumes of 2208 and 2768 vehicles/hour, respectively. Both simulation and measurement values indicate that the noise level was around 70 dB(A). The noise level at the low overpass location (10 m) was slightly higher than that at the high overpass location (17 m), indicating overpass height had an effect on the overall noise level. We assume sound waves cannot spread quickly due to the confined space, such that the noise level was slightly higher at the low overpass location. Additionally, at the same measurement location, measurement and simulation values (L_{Aeq},1h) were higher when the sound meter was 4.5 m above the ground (roughly sound receiving point on 2F) than when it was 1.5 m above the ground (roughly sound receiving point on 1F). The main reason for this was the same as that at Site A. Simulation results show that when the overpass was parallel to the freeway, the noise source, the noise level in areas near the overpass was higher via the addition of reflected noise. In other words, when the overpass and highway were parallel, the area influenced by reflected noise tended to be large.

The increase in noise level on different floors by reflected noise was 0–1.8 dB(A). Since traffic flow at this site was much lower than that at Site A, the overall noise level and reflected noise level were also much lower. Simulation results demonstrate that reflected noise had a larger effect on low floors. At high and low overpass sections, reflected noise did not affect 4F and 5F, and 3F–5F, respectively (Table 4), mainly because the heights of these floors were close to that of the overpass, such that reflected noise on these floors was insignificant. Additionally, at the low overpass section, the overall noise level on the fifth floor was significantly reduced, mainly because the fifth floor's height was the same as the overpass, and therefore the effects of reflected noises and traffic noise were not noticeable. Although the fifth floor receives traffic noise from the overpass, it has been effectively reduced by acoustic barriers on both sides of the overpass. When sound absorbing material on the overpass bottom had a sound absorption rate of 0.36 and 0.85, the decrease in reflected noise at 1F–5F was 0.3–0.8 and 0.8–2.1 dB(A), respectively. Simulation results show as the sound absorption rate of the sound absorbing material increased, noise reduction improved. The material with a sound absorption rate of 0.85 would be sufficient to eliminate reflected noise.

Table 3. Simulation values and measurement values with different overpass heights (overpass is parallel to the road).

Sound Receiving Point	L_{Aeq},1h Simulation Value (1) dB(A)	L_{Aeq},1h Measurement Value (2) dB(A)	Deviation (1)–(2) dB(A)
Overpass height (17 m) (sound meter is 1.5 m above the ground)	67.6	69.1	−1.5
Overpass height (17 m) (sound meter is 4.5 m above the ground)	70.1	70.0	0.1
Overpass height (10 m) (sound meter is 1.5 m above the ground)	69.2	69.9	−0.7
Overpass height (10 m) (sound meter is 4.5 m above the ground)	72.8	71.0	1.8

Table 4. Simulation results for the overall noise level, reflected noise, and noise reduction results for overpasses of different heights.

		High Section		Low Section	
	Floor	**L_{Aeq},1h dB(A)**	**Reflected Noise dB(A)**	**L_{Aeq},1h dB(A)**	**Reflected Noise dB(A)**
Noise level on each floor	1F	66.1	1.1	66.7	1.8
	2F	68.6	0.8	69.3	1.4
	3F	71.7	0.5	71.7	0
	4F	74.8	0	75.4	0
	5F	76.3	0	69.2	0
	Floor	Sound absorption rate 0.36	Sound absorption rate 0.85	Sound absorption rate 0.36	Sound absorption rate 0.85
Decrease in reflected noise by sound absorbing material on the bottom of the overpass	1F	−0.7	−1.8	−0.8	−2.1
	2F	−0.5	−1.3	−0.6	−1.6
	3F	−0.3	−0.8	0	0
	4F	0	0	0	0
	5F	0	0	0	0

To elucidate the effect of overpass height on reflected noise, reflected noise with different overpass heights at the low overpass section of Site B was simulated. Figure 6 shows simulation results. Reflected noise decreased as overpass height increased. With the first and second floors as examples, when overpass height was increased from the original 9.6 m to 25 m and 31 m, respectively, reflected noise was eliminated. However, increasing overpass height can be costly. Therefore, for economic reasons, we advise installing sound absorbing materials on the overpass bottom.

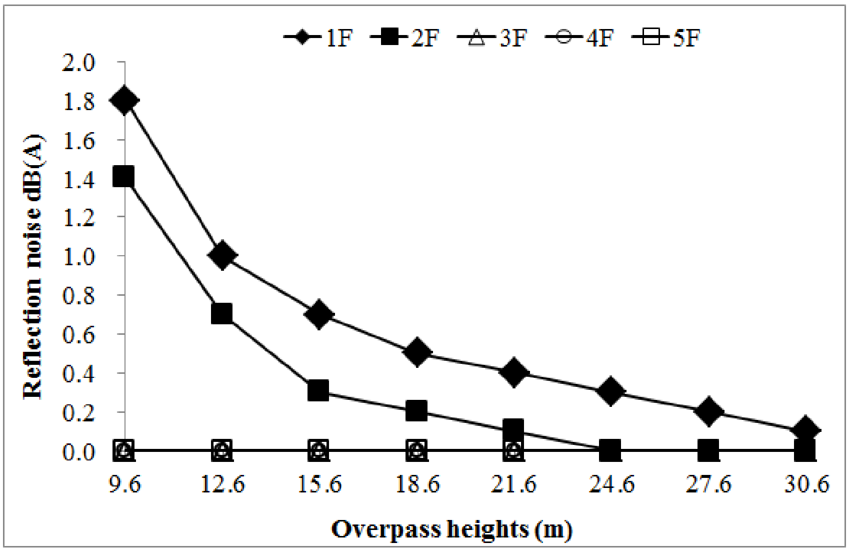

Figure 6. Simulation drawing of reflected noise change at different overpass heights (low overpass section at Site B).

3.3. Reflected Noise Analysis and Improvement Results for Different Road Structures (Overpass Going across the Noise Source Road)

Table 5 shows simulation and measurement values for different road structures. Table S3 shows Cadna A calibration input parameters for Site C. When subtracting measurement values from simulation values (L_{Aeq},1h), the deviation values at the four measurement points were 0.2–2.6 dB(A), meeting the ±3 dB(A) requirement. Thus, the sound field model can be used for simulation assessment at Site C. The noise sources at Site C were mainly northbound and southbound traffic on National Freeway No. 1, with traffic volumes at 4560 vehicles/hour and 4287 vehicles/hour, respectively. The noise level at 30 m from the overpass was lower than that at 15 m from the overpass. The reason is that the 30 m location was farther from where reflected noise was generated and therefore reflected noise was lower. On the other hand, at the same measurement location, both measurement and simulation values (L_{Aeq},1h) were higher when the sound meter was 4.5 m above the ground (roughly sound receiving point on 2F) than when it was 1.5 m above the ground (roughly sound receiving point on 1F). The likely reason is the same as that for Site A. Simulation results show that when the overpass crossed the freeway, the noise source reflected noise was generated only at the intersection of the overpass and freeway, increasing the noise level significantly in this area. That is, when the overpass crossed the freeway, reflected noise was "localized" with a small area of influence, compared with the affected areas at sites A and B.

Table 6 shows simulated results for the overall noise level, reflected noise, and improvement results for different road structures. Since the first floor of a nearby building was most vulnerable to reflected noise, change in reflected noise at different distances from the overpass was simulated for the first floor. Simulation values show that the reflected noise level was around 0.9–5.4 dB(A). Since traffic flow at this site was very high, reflected noise was considerable. In addition, the level of reflected noise decreased as distance from the overpass increased. When the distance between the simulation location and overpass increased from 15 m to 30, 45, 60, and 75 m, reflected noise was reduced by 2.6, 3.5, 4.0, and 4.5 dB(A), respectively. By simulation, when the distance from the overpass side exceeded 30 m, the level of reflected noise decreased significantly. Gozalo et al. [43] reported that under the same exposure of traffic noise, an urban area with green space had a lower level of noise annoyance than that without green space. Therefore, a proper green space buffer zone that increases the distance between the source of reflected noise and an affected area can effectively reduce reflected noise and noise annoyance of residents. When sound absorbing material had sound absorption rates of 0.36 and 0.85, the decrease in reflected noise was 0.2–1.1 and 0.6–3.6 dB(A), respectively (Table 6). As the sound absorption rate of the material on the overpass bottom increased, the noise reduction effect increased. The effect of reflection noise reduction was best when the material had a sound absorption rate of 0.85.

Table 5. Simulation values and measurement values with different road structures (overpass crossing the road).

Sound Receiving Point	L_{Aeq},1h Simulation Value (1) dB(A)	L_{Aeq},1h Measurement Value (2) dB(A)	Deviation (1)–(2) dB(A)
Distance from overpass side: 15 m (sound meter is 1.5 m above the ground)	69.9	69.7	0.2
Distance from overpass side: 15 m (sound meter is 4.5 m above the ground)	72.0	71.6	0.4
Distance from overpass side: 30 m (sound meter is 1.5 m above the ground)	68.9	66.3	2.6
Distance from overpass side: 30 m (sound meter is 4.5 m above the ground)	71.4	69.8	1.6

Table 6. Simulation results for overall noise level, reflected noise, and for different road structures (overpass crossing the road).

	Distance from Overpass	L_{Aeq},1h dB(A)	Reflected Noise dB(A)
Noise level at each distance	15 m	70.2	5.4
	30 m	69.0	2.8
	45 m	68.0	1.9
	60 m	67.5	1.4
	75 m	67.4	0.9
	Distance from overpass	Sound absorption rate 0.36	Sound absorption rate 0.85
Decrease in reflected noise by absorbing materials on the bottom of the overpass	15 m	−1.1	−3.6
	30 m	−0.7	−1.9
	45 m	−0.5	−1.3
	60 m	−0.4	−1.0
	75 m	−0.2	−0.6

4. Conclusions

This study examined the effects of noise reflected from the overpass bottom under various conditions (different bottom materials, different overpass heights, and different road structures (the overpass is perpendicular or parallel to the source road)) using onsite measurements and Cadna A simulation. The noise reduction effect of sound absorbing materials on the overpass bottom was also evaluated. Conclusions and recommendations are as follows.

1. Reflected noise from the bottom of an elevated road may be as high as 7.8 dB(A) and reflected noise increased the noise level on low floors more than on high floors.
2. Overpass height had an effect on the reflected noise level. As overpass height increased, the level of reflected noise decreased.
3. When the distance between the overpass side and a receiver exceeded 30 m, the level of reflected noise reduced significantly.
4. As the sound absorption rate of the sound absorbing material installed on the overpass bottom increased, the noise reduction effect increased. A sound absorbing material with a sound absorption rate of at least 0.60 is recommended to reduce reflected noise level.

5. By installing sound absorbing materials on the overpass bottom and providing an adequate green space buffer zone (distance between a residential area and an overpass), namely, adopting the approach of "distance attenuation + control of propagation path", the impact of reflection noises on nearby residents will be further reduced.
6. At all three investigation sites, reflected noise crossed over acoustic barriers, such that a feasible method to reduce reflected noise is to increase the height of acoustic barriers on both sides of the freeway.

The results of this study will be helpful to control existed reflected noise near overpasses and provide useful information to urban design regarding the construction of overpasses.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/8/10/1908/s1, Table S1: Cadna A calibration input parameters table (different overpass bottom materials (steel and RC)), Table S2: Cadna A calibration input parameters table (different overpass heights), Table S3: Cadna A calibration input parameters table (overpass crossing the road).

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