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Analyzing acoustic performance of a nearly-enclosed noise barrier using scale experiments and a 2.5-D BEM approach

Qiutong Li, Denis Duhamel, Yanyun Luo, Honore Yin

Abstract

This paper describes scale modelling method to measure the acoustic performance of a nearly-enclosed barrier and corresponding predictions using an existing 2.5-D Boundary Element Method(BEM) program. Preliminary investigation results show the deterioration in performance of a nearly-enclosed barrier due to the resonance effect that led to high pressure levels radiating into the surroundings via the topped opening. Absorptive material added to the inner surface of the barrier can effectively improve this phenomenon. Measurements on one-twentieth scale model of barriers, viaducts and vehicle structures were carried out outdoors under controlled conditions. The measured results show the transmission loss of transparent panels on the top were not adequate to make the measured results as high as the predictions. A modified scale model, by coating all the surfaces with rubber, was remeasured. The results from retested tests and calculations were in good agreement each other, which indicate that the 2.5-D BEM code can provide a reliable description of the acoustic performance of a nearly-enclosed barrier. Then the program was able to be employed into the investigation of barrier performance on every area with different acoustic features in the surrounding environment. As expected, the attenuation of the nearly-enclosed barrier averaged around 15 dB in the near field and around 10 dB in the far field. The number effect of incoherent point sources on the performance is discussed as well for the study of railway traffic noise. The increased number of incoherent point sources can result in smoother and lower attenuations for the whole sound field.

Keywords: Enclosed noise barrier, scale model measurement, BEM

1 1. Introduction

2 In general, noise barriers are built on the side of viaducts to reduce ur-
3 ban railway traffic noise pollution. The associated acoustic performance is
4 thought to depend largely on their height and the relative distance between
5 the source, the barrier and receiver positions[1]. There is almost no change
6 for the latter since the predominant source for urban railway traffic is located
7 on the place of wheel-rail interaction, and the barrier position, varying with
8 changes of width of the viaduct, remains basically unchanged. To improve
9 the performance devices installed on the top of the barrier are sometimes
10 introduced instead of the height increase. Among all the barriers on the
11 market, enclosed types are common solutions to improve the most. LI. et
12 al.[2] studied on the noise reduction of semi- or fully-enclosed barriers of high
13 speed railways using the full-scale modelling. The results showed that the
14 attenuation of fully-enclosed metal noise barrier with composite sound ab-
15 sorption plates was up to 25 dB(A) at 7.5m distance from the track central
16 line. However, the barrier cannot be fully-enclosed when consider the fire
17 safety. Since the space inside an enclosed barrier is very small when a train
18 passes by, an opening, commonly with a two-meter height, is designed on the
19 top so that smoke can be emitted when fire occurs. In the present study this
20 kind of barrier is called a nearly-enclosed barrier, one of the prototypes de-
21 picted in Figure 1. The two arched parts on the top are made of 6.5-mm-thick
22 PC panels that allows in natural light and to reduce limitation of drivers'
23 view[3]. One of the important issues is the sufficiency of the sound insula-
24 tion property of such material that is required to achieve suitable acoustical
25 performance.

26 Another for that is the multiple reflections between two axisymmetric
27 parts and between the extremely high barrier and the vehicle surface that
28 significantly degrade barrier performance. Watts[4] found a reflecting wall
29 with a 2m height fixed on the source side could result in a reduction of 4
30 dB(A) in the insertion loss of a sound barrier of the same height. More
31 seriously in our study, the acoustical domain bounded by a nearly-enclosed
32 barrier can be considered as a room with a door or an open duct, and then
33 the sound field within such domain can be dominated by acoustic resonance.
34 Under the influence of this effect high pressure amplitudes may be observed
35 at the resonant frequencies leading to the significant degradation of barrier
36 performance. In the parametric investigation of the performance of multiple
37 edge highway noise barriers, D.J. Oldham and C.A. Egan[5] observed the

38 acoustic resonance in the air in the gap between an edge and the barrier
39 face resulting in the negative relative insertion loss for the configurations
40 involving reflective edges located on the source side of the barrier. In par-
41 allel with this development, Yang et al.[6] firstly proposed the resonance
42 effect of the trapped modes to explain the deterioration in performance of
43 a conventional barrier due to the reflecting surface. To solve the multiple
44 reflections and the peak sound pressures governed by resonance, a tilted bar-
45 rier was proposed[7, 8] as a solution with a slope of ten degrees gaining the
46 best profit and a wave-trapping barrier was proposed[6] effectively in reduc-
47 ing the deterioration at peak frequencies. Furthermore, absorptive materials
48 were employed on the surface of reflective barrier near the source being able
49 to reduce the deterioration with highly efficiency[9].

50 A number of studies have made clear the importance of "T", "Y" and
51 other top devices in improving the diffraction reduction of barriers but there
52 is little research as a specific guidance that can be applied to the problems
53 discussed in this paper. Thus the objective of this research is to analyze
54 acoustic performance of a nearly-enclosed barrier using numerical and exper-
55 imental method. An existing 2.5-D BEM program was used to characterise
56 the acoustic performance of a nearly-enclosed barrier on every area with dif-
57 ferent acoustic features in the surrounding environment. Its reliability was
58 validated by comparing predictions with measured results from scale model
59 tests. The scale modelling technique is more efficient and more accurate to
60 not only investigate barrier performance, but also to realize the effect of re-
61 lated parameters on the acoustic performance. By using scale experiments
62 and 2.5-D BEM approach the efficiency of noise reduction of constructed
63 panels and the number effect of incoherent point source are also studied.

64 Section 1 of this paper briefly introduces a nearly-enclosed barrier com-
65 monly applied on the city viaduct railway traffic system and some relevant
66 issues need to be resolved. Section 2 presents a 2.5-D BEM model obtained
67 from a real prototype. The resonance effect of acoustic modes on barrier
68 performance is also described by a preliminary investigation in this section.
69 Section 3 validates the numerical model by a series of scale measurements.
70 As a result of the measured results much lower than those predictions, the
71 sound insulation property of transparent material is discussed in this sec-
72 tion. Then a series of remeasurement on the modified model is described
73 and the results give confidence in the subsequent predictions. Section 4 pre-
74 dicted acoustic performance of a nearly-enclosed barrier by using 2.5-D BEM
75 modelling. The attenuation of barrier located at several receiver positions

76 in the near and far field comparing different source types are discussed in
77 detail, and all the predicted results are summarized. Section 5 gives a brief
78 conclusion in this paper.

79 **2. 2.5-D Boundary element modelling**

80 Based on the direct formulation of Boundary Element Method(BEM), the
81 2-D, 2.5-D and 3-D BEM numerical methods were developed and detailed in
82 [10–15]. In the 2-D numerical simulation, a 2-D point source is commonly
83 approximated as an infinite coherent line source in three dimensions; the bar-
84 rier and other obstacles are defined with the cross-section remaining constant
85 and infinite along a direction perpendicular to the section plane. 2.5-D BEM
86 method gives a chance to allow the use of other sources like a point source or
87 an incoherent line source but remain the geometrical characteristics of all the
88 obstacles. DUHAMEL[14] compared these three source types and figured out
89 that the results predicted for a coherent line source were basically equivalent
90 to that for a point source while incoherent line source showed considerable
91 difference in frequency domain. P. Jean et al.[15] emphasized the importance
92 of source type in the numerical modelling based on the calculation of 2.5-D
93 BEM approach. They found the attenuation of conventional noise barriers
94 for a coherent line source was much higher than that for an incoherent line
95 source. Considering that the road/railway traffic noise is commonly assumed
96 as one or more than one incoherent line sources[3, 12, 15, 16], using 2-D
97 BEM modelling with coherent line sources must result in the overestimation
98 of barrier performance. As a consequence, it was decided to carry out the
99 calculations with a 2.5-D model using different numbers of incoherent point
100 sources.

101 To validate a model nearly-enclosed barrier in three dimensions by BEM
102 requires a certain amount of time for the high complexity of the computing
103 process due to the complex geometry of the barrier. Based on the numerical
104 method proposed in [14], a 2.5-D existing program was used to carry out 3-D
105 boundary element calculations from solutions of problems defined in two-
106 dimensional domains outside the associated cross-section. By using BEM to
107 solve the acoustic problems in two-dimensional domains, the efficiency of the
108 calculation is considerably improved. At the beginning of 2.5-D calculation,
109 the source is assumed as coherent line source perpendicular to the page plane
110 at first, which maintains the two-dimensional nature of the model. Subse-
111 quently by Fourier-like transformation the sound pressure fields created by

112 the coherent line source for the whole frequency spectrum will be converted
113 into those radiated by a point source in three dimensions. The third position
114 of the point source, defined relative to the plane where the two-dimensional
115 calculation has been done, was considered in the existing program as well.
116 Hence it was possible to calculate sound pressure for a line of such incoherent
117 point sources.

118 The 2.5-D model of a nearly-enclosed barrier was obtained from the real
119 prototype located on the viaduct of Metro 1 in Ningbo city, China, as shown
120 in Figure 1. The noise barrier and the viaduct were assumed infinite uni-
121 form in construction along their length. In reality the barriers are installed
122 on the viaducts so that there is no gap between the barriers and viaducts.
123 However, on the basis of the BEM principle the distance between these two
124 independent boundaries is at least larger than the element size[17]. Thus,
125 this requires the geometry removal of the connections between them and
126 therefore the boundaries of the viaduct and the barrier were integrated as a
127 whole. These changes in the model are illustrated in Figure 2. The shape
128 of vehicle source was simplified as a rectangle based on measurements of the
129 stock Type B of China Railway Rolling Stock. The height assumed was 3.7
130 m and the width was 2.8m. It can be seen from Figure 2 that the source was
131 placed at the outside wheel-rail interaction position. All the boundaries of
132 the vehicle structure were made acoustically rigid. Taking into account re-
133 flections from the ground, the reflection from the image source symmetric to
134 the source was also introduced into the model and the height of the viaduct
135 above ground was 10 m.

To improve the precision requirement, the size of quadratic order ele-



(a) Inside the barrier

(b) Outside the barrier

Figure 1: A prototype of the nearly-enclosed barrier located in Ningbo, China

136
137 ment was defined as one tenth of the minimum wavelength. Furthermore,

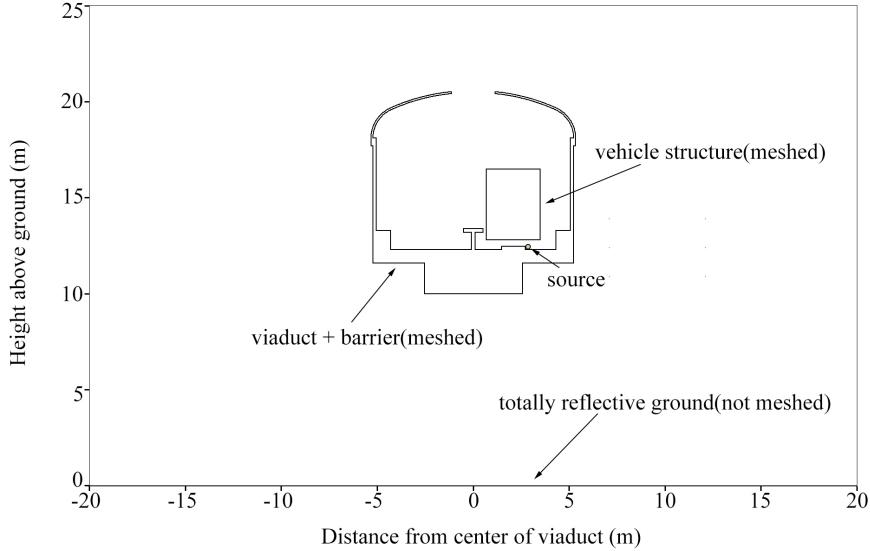


Figure 2: Numerical model for nearly-enclosed barriers on urban railway viaducts solved by 2.5-D BEM program

¹³⁸ numerical predictions were calculated at third octave frequencies from 50 Hz
¹³⁹ to 1000 Hz.

¹⁴⁰ A preliminary investigation was performed with the BEM predictions to
¹⁴¹ understand the mechanism of the multiple reflections inside a nearly-enclosed
¹⁴² barrier. In Figure 3, the blue areas represent pressure levels for the coher-
¹⁴³ ent line source as a function of frequency, fluctuating violently with a huge
¹⁴⁴ number of sharp-pointed peaks. Although the peak value decreases with in-
¹⁴⁵ creasing of frequency, with the rise in the number these peaks progressively
¹⁴⁶ dominate the sound pressure at a given receiver. Similar trends can be ob-
¹⁴⁷ served as well for the one-point source by the green areas, and these peaks
¹⁴⁸ retain their relative high levels at the similar frequencies. These peak levels
¹⁴⁹ would directly cause the deterioration of barrier performance that could not
¹⁵⁰ be ignored. According to the principle of resonance modes as referred in
¹⁵¹ Section 1, several acoustic modes of the air cavity inside the barrier fully en-
¹⁵² closed by Neumann boundaries, which corresponds the sound pressure level
¹⁵³ distribution at peak frequencies marked by red circles in Figure 3, are de-
¹⁵⁴ picted. Figure 4&5 shows the 2D BEM results and the FEM acoustic modes.
¹⁵⁵ Good agreements on the contours and the peak frequency values are easily
¹⁵⁶ observable, which means these peak levels in the frequency domain were the

157 result of the resonance effect of the open-air cavity. Besides that, it is significant
 158 to note that the topped opening was not able to eliminate the resonance effect,
 159 but also leak high pressure levels into the surrounding region, thereby impacting
 160 seriously the noise reduction ability of the nearly-enclosed barrier.
 161 If some absorptive treatments are further added to the inner surface of the barrier, it is effective to improve the performance.

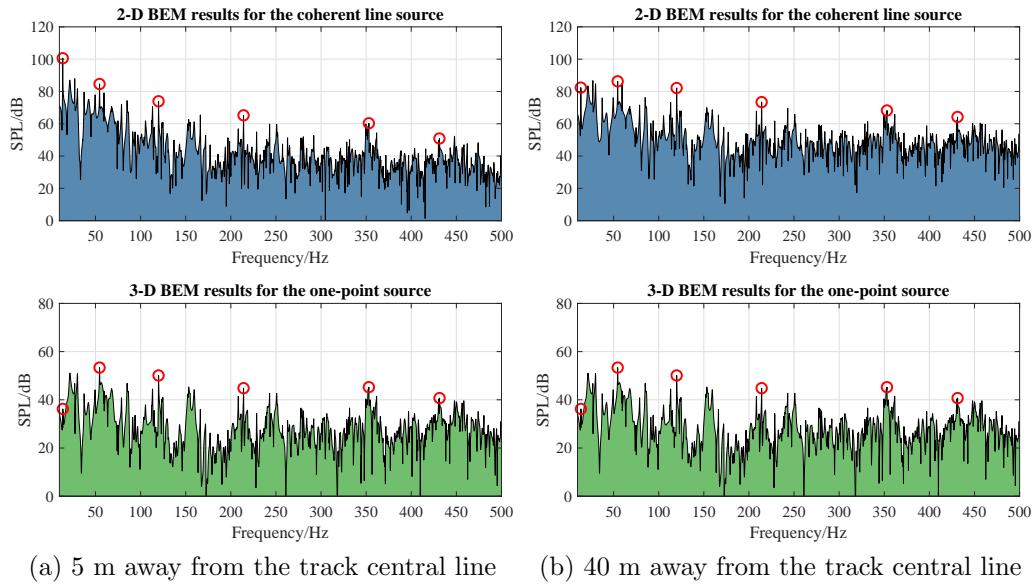


Figure 3: The spectrum of sound pressure levels in the near and far field governed by the nearly-enclosed barrier(the receivers are positioned at the height of source)

162

163 3. Scale model measurement

164 To validate the predicted results for a nearly-enclosed barrier, the method
 165 of acoustic scale modelling was introduced. Scale model measurement has
 166 strict request to measurement environment. The test site has to be deliberately
 167 left as open as possible in order to emphasize the diffraction sound
 168 generated by the barrier model and prevent reflection sound caused by any
 169 reflecting surface close to the model from affecting the measured results. The
 170 site was finally selected as shown in Figure 6(a), which fully met the requirement
 171 specified previously. Considering the site limitations, the scale of the
 172 barrier model in our case was determined as 1:20.

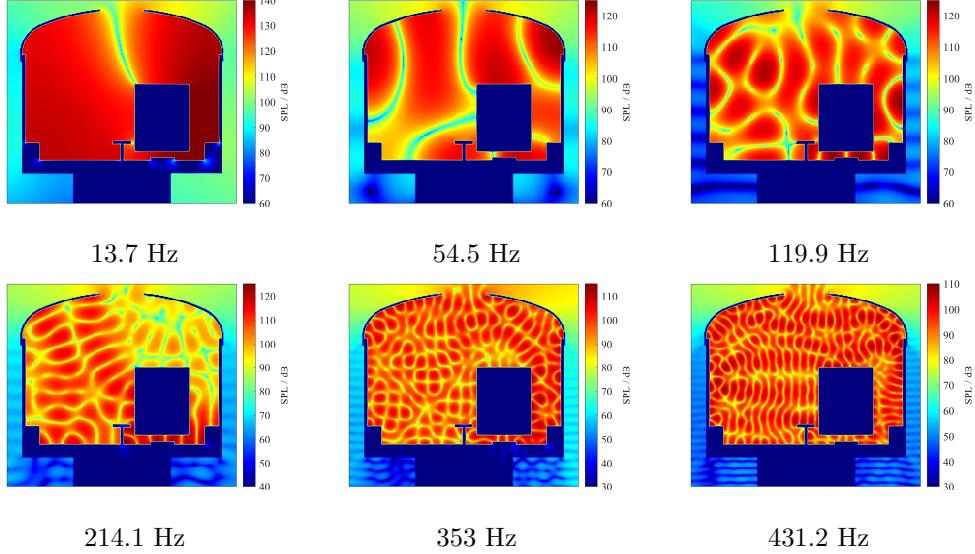


Figure 4: Pressure level distribution inside the barrier of 2-D BEM model

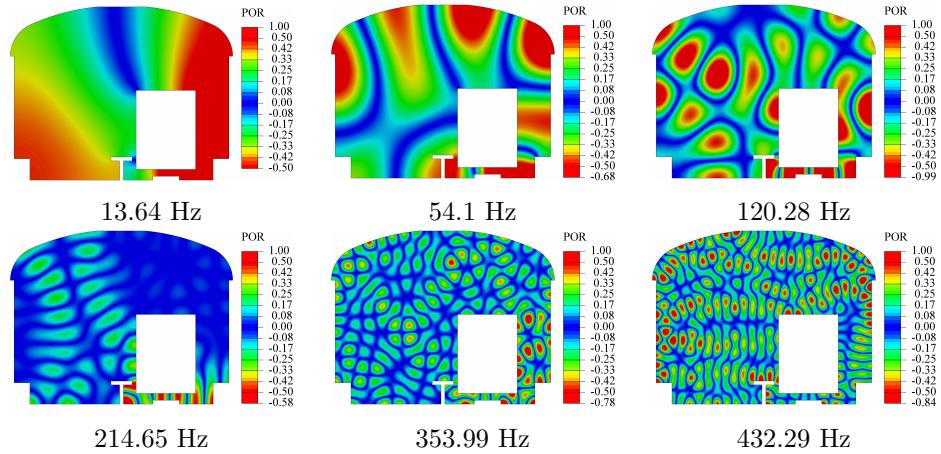


Figure 5: Several acoustic modes of the air cavity fully enclosed by the Neumann boundaries inside the 2.5-D BEM model of the nearly-enclosed barrier

173 3.1. Measurement apparatus

174 Generally loudspeakers and microphones are the indispensable transduc-
 175 ers in an acoustic experiment. In order to send the electrical audio signal to
 176 the loudspeaker and receive it from the microphone synchronously, a collec-
 177 tion of electronic apparatus was prepared. Miniature speakers with the size

178 of less than 1 mm^3 were chosen in our study since the space where the speaker
 179 located was less than 10 cm^3 (approximately the size of an eraser). Commonly
 180 a normal-sized loudspeaker has a diameter of at least 30 mm , which is too
 181 large to be placed inside this model. The spectrum of the speaker was mea-
 182 sured at several angles. It was found to be omni-directional when towards
 183 to the microphone. During the formal measurement for each test several
 184 employed loudspeakers emitted simultaneously white noise with one of the
 185 third octave spectrum from the signal output module. For these miniature
 186 loudspeakers the amplifiers and the power supply were selected accordingly.
 187 On the other hand, the highly sensitive B&K microphones 4189-A-021 sat-
 188 isfy the requirements of such high-precision, free-field measurement. They
 189 were powered from the supply offered by the DAQ signal output module.
 190 All the electronic apparatus were put under the model above ground, which
 191 did not appear in the transmitting path between the loudspeakers and the
 192 microphones affecting the measured results.

193 A VI project was designed in the LabVIEW development environment
 194 to transmit\receive electric signals. Figure 6(b) illustrates the signal flow
 195 graph of the measurement. It can be seen clearly that the original source
 196 signal was generated by the VI project from the laptop, transmitting to the
 197 output module, via the amplifier to the loudspeaker. In the meantime, sound
 198 pressure signal was received and preamplified by the microphone, via the in-
 199 put module back to the laptop, finally saved by the VI project. It is worth
 200 emphasizing that the VI project did not only play a role as a signal generator
 201 for activating the loudspeaker, it also undertook that of receiving, saving and
 analysing the signals from the receivers.

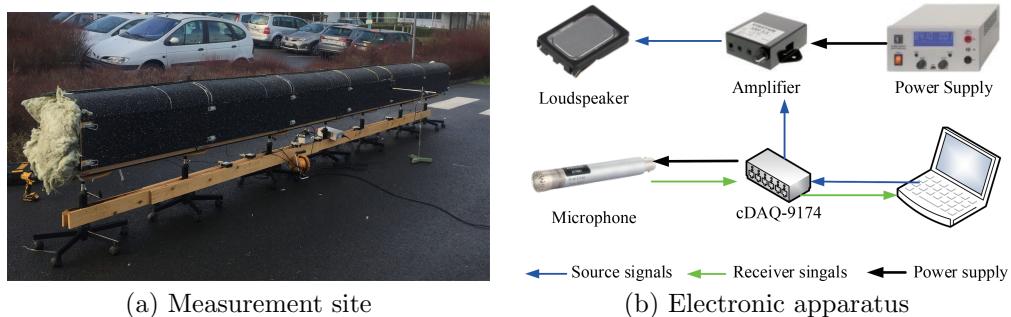


Figure 6: Scale measurement preparation

203 *3.2. Scale model measurements*

204 All barriers used in the experiment were a twentieth of the full scale nu-
205 mercial models. It was necessary to build simplified models for the complex
206 structure so that sound diffraction towards the barrier would dominate at-
207 tenuation measurements, facilitating comparison with the predictions from
208 the BEM model which being 2.5-D in the space with infinitely long barriers.
209 The tests were made in six configurations, of which the cross-sections were
210 shown in Figure 7,

- 211 • Tests with viaducts and nearly-enclosed barriers(Figure 7(a1)(a2)).
212 • Tests with viaducts and double-straight barriers(Figure 7(b1)(b2)).
213 • Tests with viaducts(Figure 7(c1)(c2)).

214 The blue parts represent PC panels with a thickness of 5 mm and the brown
215 parts are 9-mm-thick assembled wood planks. Tests were made with and
216 without vehicle structures which were one twentieth the practicable 3.7x2.8
217 m² in full scale.

218 The 1:20 scale model was an assembly of six sections the length of each
219 section being defined as 1 m since the metro vehicle is 19 m long and each
220 train has six vehicles in reality. However, sound transmitting over the two
221 ends of the model to the microphone must affect sound pressure level at the
222 receivers. In order to reduce the end effect as much as possible, both barrier
223 ends were filled with mineral wool to absorb sound(shown in Figure 6(a)).

224 There were twelve loudspeakers arrayed along the length of the six-section
225 model. Each section of the model had two sources placed exactly at the po-
226 sition of each vehicle wheel in reality. The position in the cross section was
227 close to the location of the wheel-rail interaction, in accord with that of the
228 point source in the 2.5-D BEM model. A time-history signal of white noise
229 was taken as the input of the sound source to the loudspeaker. Each of
230 the signals was individually coherent but mutually incoherent to the others.
231 Figure 8 and Table 1 present these co-ordinates and the numbers of the loud-
232 speakers. The sampling position for the microphone was placed exactly at
233 the cross-section where the 7th loudspeaker positioned.

234 Two sets of tests were taken to determine the third octave sound pressure
235 levels outside the barriers. Tests were completed with the viaduct but with-
236 out barriers(Figure 7(c1)(c2)) so that the attenuation could be calculated
237 as the difference between the sound pressures measured in the presence and
238 absence of barriers. Tests with viaducts and double-straight barriers(Figure

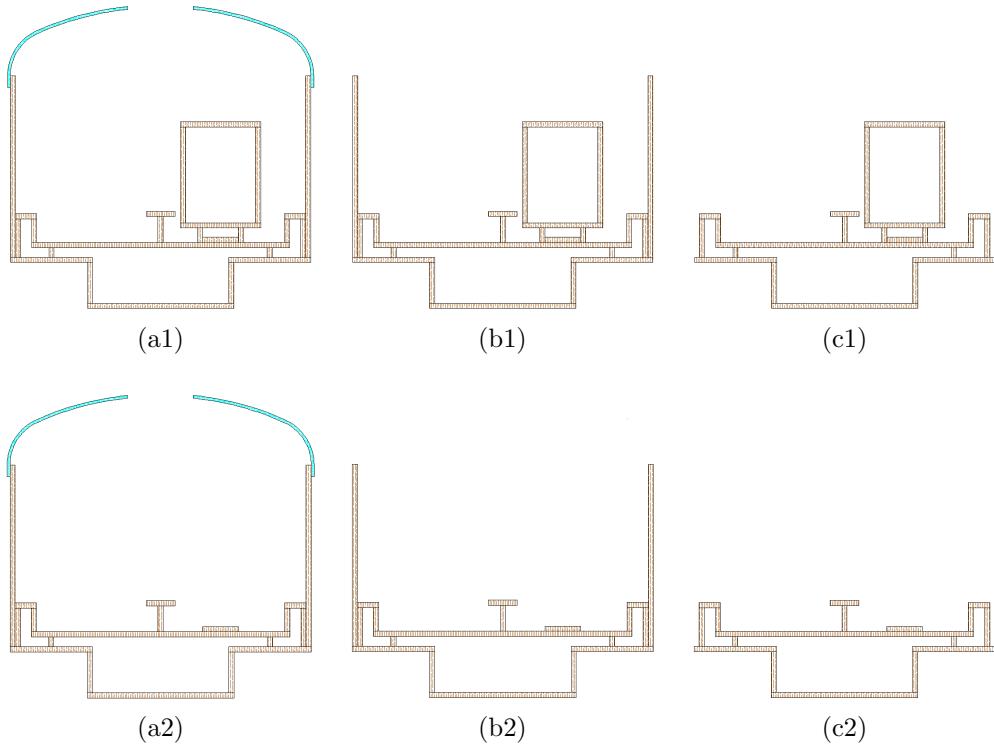


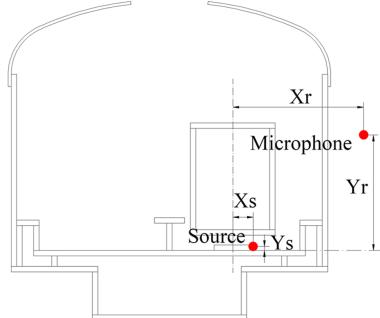
Figure 7: All the configurations of tested models. The upper row shows the models with vehicle structures and the lower row shows the models without vehicle structures.

239 7(b1)(b2)) were completed as well in order to understand the sound insulation
 240 property of the PC panels. In addition, the attenuations at the third
 241 octave band frequency from 1000 Hz to 20 kHz were tested to validate the
 2.5-D BEM predictions from 50 Hz to 1000 Hz.

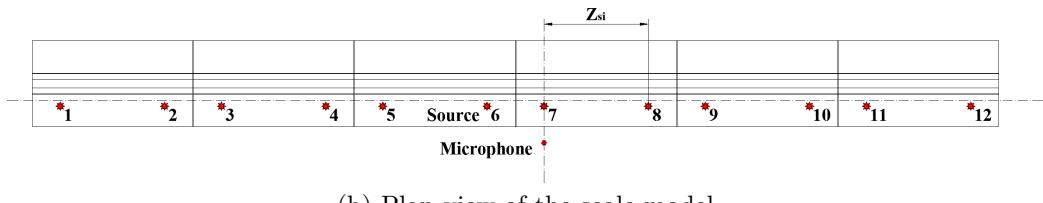
Table 1: Positions of loudspeakers and microphone in three co-ordinates(cm)

Loudspeaker			Microphone		
X _s	Y _s	Z _{si} (i=1,2,...,12)	X _r	Y _r	Z _r
3.6	0.5	-296.7, -233.7, -197.8, -134.8, -98.9, -35.9, 0, 63.0, 98.9, 161.9, 197.8, 260.8	25.6	19.0	0

242



(a) Cross-section of the scale model



(b) Plan view of the scale model

Figure 8: Experimental arrangement for the nearly-enclosed scale barrier

243 3.3. Comparisons with BEM predictions

*244 Predictions were carried out for the nearly-enclosed and double-straight
245 barriers using the 2.5-D BEM program. The number of the incoherent point
246 sources defined was one(the 7th) at first. Subsequently when numerical pre-
247 dictions were validated by measured results, the number would add up to
248 four(the 5th, 6th, 7th and 8th) and finally to all twelve.*

*249 For one point source facing the microphone, Figure 9(a) shows plots of
250 measured and predicted attenuations by the third octave band in the case of
251 the double-straight barriers on the viaduct with and without vehicles. The
252 predicted third octave source spectra was adjusted in the analysis so that
253 the effective source spectra used in the BEM and scale models were identical
254 (note that further frequencies in Section 3 will be given in the scale 1:20
255 for the sake of clarity). It is clear that as expected there is good agreement
256 for each comparison between the measured results and those predicted by
257 the 2.5-D BEM approach. The small deviation between the measured and
258 predicted results is normal and permissible due to the non-idealised point
259 source used for measurements.*

260 Figure 9(b) shows the compared results for the nearly-enclosed barrier

on the viaduct. It is worth noting that the measured attenuations are much lower than those predictions regardless of the vehicle structures present, especially for high frequencies. And these measured results are as high as those measured for the double-straight type. With the finding of these significant differences between the measured and predicted results for the nearly-enclosed barrier, a strong argument can be made that the PC panels on the top were not considered to be acoustically rigid. This finding might be due to the sound insulation properties of the PC panels and wood planks which were not sufficiently high to reduce sound transmission through the nearly-enclosed barrier.

3.4. Sound insulation problem

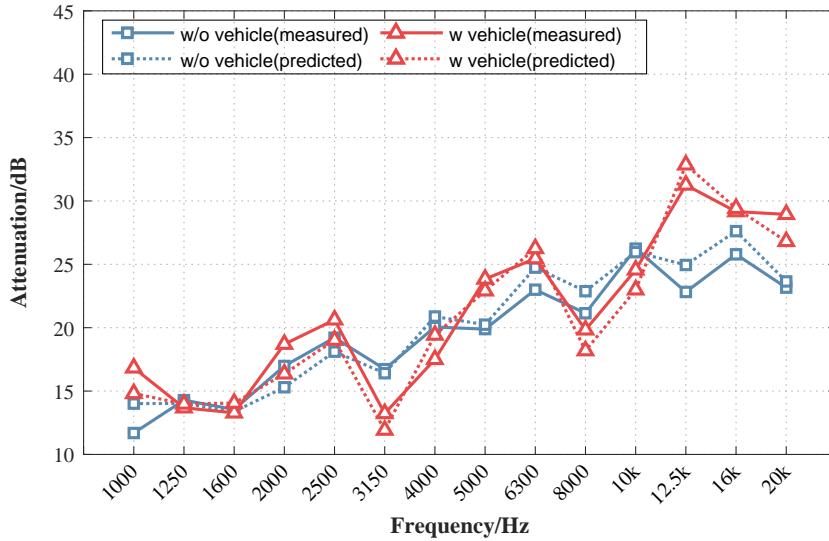
The sound insulation propertas found abovey of material is usually evaluated by an acoustic physical term[18] i.e., sound transmission loss known as TL which is defined as 20 times the logarithm of the ratio of the acoustic pressure associated with the incident wave and that of the transmitted wave.

In terms of energy transfer, attenuation of the sound barrier(also known as Insertion Loss) depends precisely on the energy distribution of sound diffraction over the top, transmission through the barrier and reflection bounced off its surface. Considering the effect of ground absorption, the practical attenuation of the sound barrier is given as,

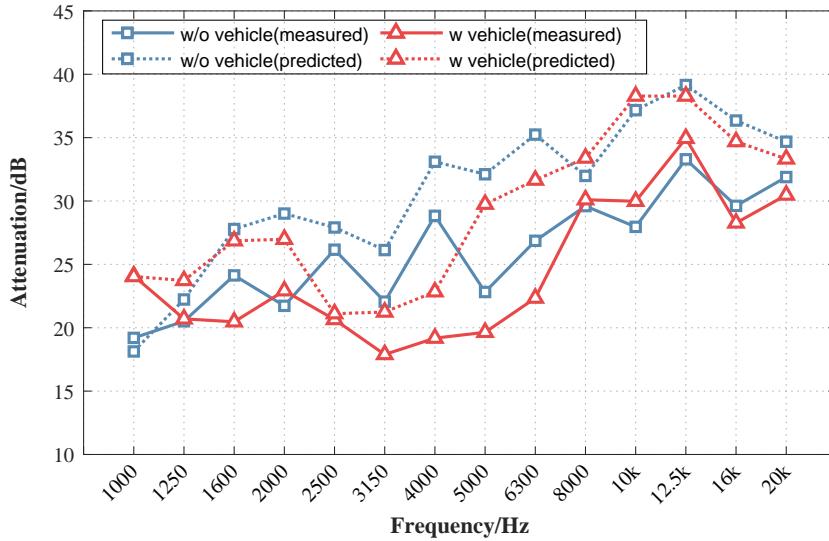
$$IL = A_d - C_t - C_r - C_G \quad (1)$$

where A_d denotes diffraction attenuation of the barrier top and side edges, which is the most important physical phenomenon in the noise reduction process. C_t is the correction value for sound transmission through the barrier, C_r is the correction for the sound reflection bounce off the barrier and C_G is the correction for ground absorption.

Typically, the diffraction attenuation A_d is much lower than the TL of high-density materials employed in the construction of the barrier, at least 10 dB. And in such case the correction for sound transmission C_t is negligible in the overall performance of the barrier. However, the predicted attenuations of the nearly-enclosed barrier have been found greatly higher than 20 dB over the frequency range of 1000 Hz-20 kHz shown in Figure 9(b). These values might be extremely close to those for the Tls of the employed materials so that the correction C_t could not be ignored in the calculation of the insertion loss. According to Eq (1) the measured attenuations were therefore lower



(a) Double-straight barrier on the viaduct



(b) Nearly-enclosed barrier on the viaduct

Figure 9: Measured and predicted attenuations for the model(a) double-straight barrier(Figure 7(b1)(b2)); (b) nearly-enclosed barrier(figure 7(a1)(a2))

295 than our expectations.

296 Since the barrier attenuation is frequency dependent and so is the impact

of transmission loss, to better understand their relationship, the comparisons for high frequencies between the predicted attenuations for the nearly-enclosed and the double-straight barrier and the measured TLs for the PC panels are illustrated in Figure 10. The blue and red curves without symbols represent the TLs for PC panels measured by Woo-Mi Lee et al.[19] with a thickness of 4 mm and 8 mm, respectively. On account of the thickness of the PC panel in our test being 5 mm, its TL curve must be sensibly lying in the region between these two curves. At the frequency higher than 4000 Hz, the value of TL theoretically tends to increase 6 dB per octave band. As a consequence, the approximated transmission loss of the employed PC panels in our test was estimated reasonably for each third-octave band of interest according to the discussion above, which is represented by the green dotted line shown in Figure 10. The blue and red curves with rectangular symbols in Figure 10 represent the predicted attenuations for the nearly-enclosed and double-straight barrier, respectively. It is obvious that at frequencies from 1000 Hz to 2000 Hz and from 4000 Hz to 12.5 kHz the approximated TLs are quite close to the predicted attenuations for the nearly-enclosed type, but much higher than those for the double-straight type by at least 10 dB. Hence the correction term of sound transmission must be taken into account and in such case the boundary condition of two arched PC panels cannot be considered as totally reflected in the BEM model for the nearly-enclosed barrier. Therefore, we can conclude that the insufficient insulation property of the PC panels must be the foremost reason for the considerable differences between the predicted and measured results mentioned previously for the nearly-enclosed barrier.

To improve the sound insulation property of the arched parts for the nearly-enclosed barrier so that better measured attenuations could be tested, a kind of material that provides good sound insulation as well as flexibility was needed. The transmission loss of a typical single-layer material is theoretically divided into three distinct performance regions developed from the frequency range: I. stiffness and resonance region, II. mass region and III. coincidence region. Region I typically ranges below 200 Hz[20] where the TL is controlled by the stiffness and the resonance frequency of the material. In Region II the relationship between TL and frequency is mainly controlled by the mass of material, which is known as the mass law: each time the mass is doubled the TL increases 6 dB. This law continues to meet the critical frequency f_c at which sound waves incidents are able to efficiently transfer energy to the panel. This phenomenon is called the "coincident effect" which

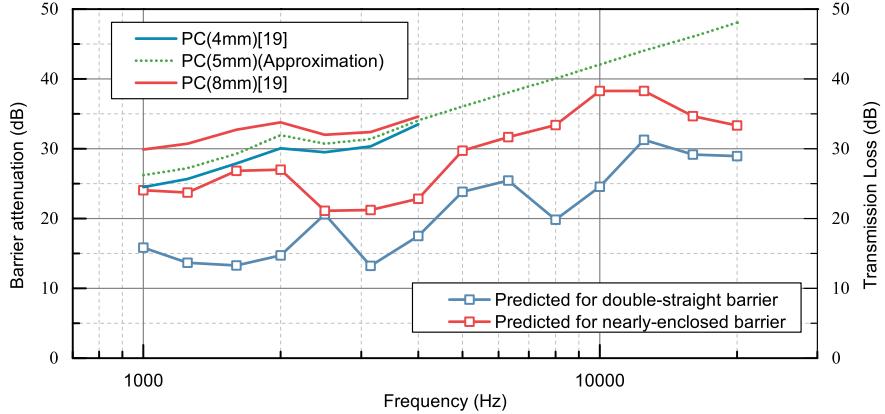


Figure 10: Comparison between the predicted attenuations of barriers and the TLs of PC panels

335 severely influences the sound insulation performance of the material. The
 336 critical frequency for a single-layer isotropic homogenous material is defined
 337 as,

$$f_c = \frac{c^2}{2\pi t} \sqrt{\frac{12\rho_m (1 - \sigma^2)}{E}} \quad (2)$$

338 where c denotes sound speed, t is the thickness of material and ρ_m is mass of
 339 the panel per unit surface area. E and σ are Young's modulus and Poisson's
 340 ratio of the material, respectively.

341 Taking for instance the 5-mm-thick PC panel with an average density of
 342 1.2 g/cm^3 employed in the scale measurement, the TL fluctuates violently in
 343 Region I, then increases by 6 dB per octave in Region II and suddenly declines
 344 significantly when approaching critical frequency. At higher frequencies the
 345 TL continues to increase by 6 dB per octave again in Region III. The critical
 346 frequency for the PC panel equals approximately 3200 Hz calculated by Eq.
 347 2. The value of critical frequency is in the range of interest, which means the
 348 employed PC panels in the scale measurement showed their sound insulation
 349 performance not only in Region II but also in Region III. Recall from Figure
 350 10 that in Region II below 3200 Hz the differences between the TLs and the
 351 predicted attenuations for the nearly-enclosed model were less than 10 dB,
 352 and in Region III the loss of TL caused by the coincident effect leads the TL
 353 much closer to the increased attenuation with increasing frequency. Once
 354 more, the further analysis based on the sound insulation theory proves that
 355 the PC panels employed in our test were not able to sufficiently insulate the

356 traffic noise.

357 From these findings we can summarize that the material with high density
358 has a good sound insulation property due to the mass law. On the other hand,
359 with high critical frequency the material shows its TL performance in the test
360 almost in Region II to avoid the coincident effect. Hence it is better to select
361 a kind of transparent material with high density, high critical frequency and
362 high flexibility for the arched shape. According to this description, the 10-
363 millimetre-thick rubber was chosen. The TL of the arched parts must be
364 improved considerably by the heavy mass owing to the high thickness of
365 rubber. Although the density can be expected to be between 0.96 g/cm^3
366 and 1.3 g/cm^3 only as large as that for the PC panels, with a low Young's
367 Modulus($0.001\text{-}0.0022\text{ GPa}$) its critical frequency can be up to over 40 kHz so
368 that its TL performs only by the mass law in the scale model measurement.
369 Furthermore, it is quite easy to reshape. Thus, it was possible to reduce the
370 differences between measured and predicted results by the rubber covering
371 with no need to worry about the transparency of the material.

372 For the sake of comparison between the scale model with and without
373 rubber, the rubber was only applied to coat the whole model of barrier, not
374 to act as the alternative to any existing materials constructing the barrier.
375 Figure 6(a) shows its application in our scale model measurement.

376 3.5. Effect of rubber covering

377 In order to improve the sound insulation, repeated scale tests with addi-
378 tional 10-mm-thick rubber covering on the outer surface of the model were
379 carried out. Figure 11 illustrates all the configurations of the tested mod-
380 els with the rubber covering. The black parts represent the rubber coating
381 on all the outer surfaces of the barrier. In addition, to test the effect to
382 the nearly-enclosed barrier(Figure 11(d1)(d2)), a comparison for the double-
383 straight barrier between the model with and without the rubber covering was
384 made as well. Figure 12 compares the measured results with the correspon-
385 ding BEM predictions for the double-straight model and the nearly-enclosed
386 barrier, respectively. Identically to the previous observations, the measured
387 results for the double-straight barrier with the rubber covering correspond to
388 the 2.5-D BEM predictions, and the differences between the measured results
389 and the predictions are a little smaller than those for the case without the
390 rubber covering(Figure 9(a)). This proves the employed wood planks were
391 sufficiently thick to insulate sound when the barrier shape was straight. And
392 with the help of the rubber covering the improvement was negligible. Then

393 to compare with the nearly-enclosed barrier it is encouraging that with the
 394 addition of the rubber covering the agreement between the measured and pre-
 395 dicted results was obviously improved comparing with that shown in Figure
 396 9(b) . This agreement provides very strong evidence that the employed PC
 397 panels cannot be assumed to be totally reflective panels to preventing sound
 398 from transmitting through when the barrier has a nearly-enclosed shape, and
 399 adding a cover of material with good sound insulation to the surface of the
 400 PC panels is a practicable way to improve the barrier attenuation, to bring
 401 it close to the expectation of 2.5-D BEM model.

402 As a result, it can be concluded that generally there is good agreement
 403 between the measured results obtained in the scale model with the rubber
 404 covering and those predicted by the 2.5-D BEM model of the nearly-enclosed
 405 barrier.

On the basis of the agreement between the measured results and predic-

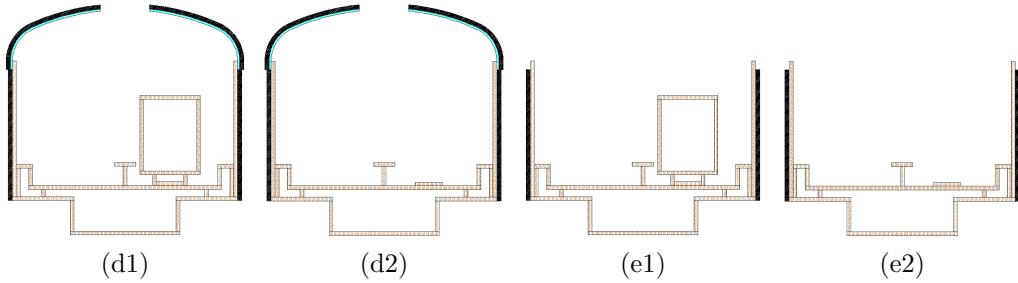
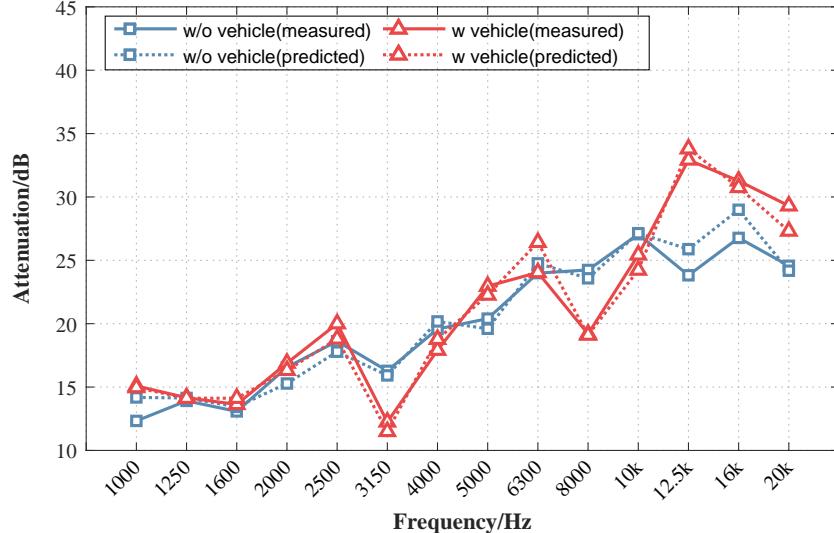


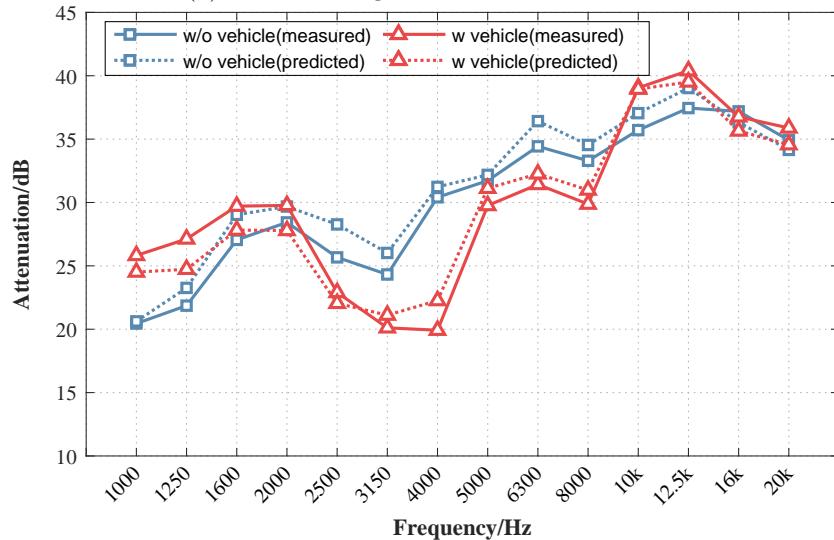
Figure 11: The configurations of the tested models with the rubber covering

406 tions for the nearly-enclosed barrier, the number effect of incoherent point
 407 sources on the barrier attenuation was analyzed. In order to validate the
 408 2.5-D BEM predictions with several incoherent point sources the number
 409 of loudspeakers was changed as mentioned previously. Figure 13 provides
 410 the information about the results for different numbers of incoherent point
 411 sources for the nearly-enclosed barrier. Before the discussion on the number
 412 effect of incoherent point sources, it is necessary as a starting point to verify
 413 the predictions by the measured results. Apparently each comparison shows
 414 good agreement, as our expectation. Then, we found that the curves in Fig-
 415 ure 13 vary widely with increased frequency: some are extremely fluctuating,
 416 while others tend to smooth.

418 In Figure 13, it is easy to understand the growth of attenuation fluctu-
 419 ates seriously with frequency for one point source(blue curves). And yet it is



(a) Double-straight barrier on the viaduct



(b) Nearly-enclosed barrier on the viaduct

Figure 12: Measured and predicted attenuations for the model with the rubber covering (a) double-straight barrier (Figure 11(e1)(e2)); (b) nearly-enclosed barrier (Figure 11(d1)(d2))

420 interesting that the attenuation tends to increase smoothly as the number of
 421 incoherent point sources increases to four (red curves). When increased to the
 422 maximum number of sources (green curves), the attenuations have a visible
 423 decline at each frequency band in comparison with those of four-point source.

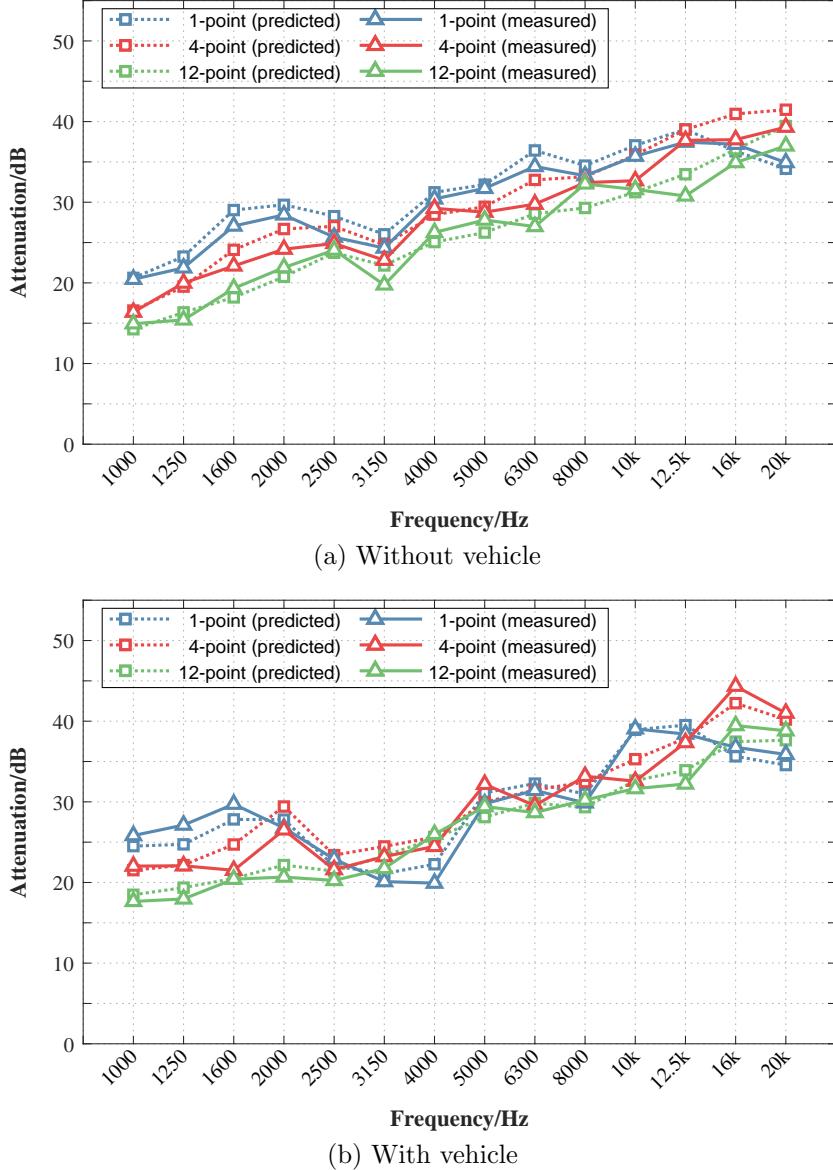


Figure 13: Measured and predicted attenuation for the nearly-enclosed barrier: (a) without vehicle(Figure 11(d2)); (b) with vehicle(Figure 11(d1))

424 In addition, the comparison of the results between the model with and without
 425 vehicle structures was also considered. The frequency-attenuation
 426 curves with the vehicle structures(Figure 13(b)) fluctuate much more than

427 those without the vehicles(Figure 13(a)), even for the smoothest curves cor-
428 responding to the twelve incoherent point sources. This is due to the multiple
429 reflection between the vehicle structure and the inner surface of the barrier,
430 which can be reduced by treating the inner surface with an absorbent mate-
431 rial.

432 All the findings in the scale measurement for the nearly-enclosed model
433 with a rubber covering demonstrate good agreement with those predicted by
434 the 2.5-D BEM approach for each the third octave band from 1000 Hz to
435 20 kHz. To summarize, it can be assumed that the acoustic performance of
436 the nearly-enclosed barrier investigated by the 2.5-D BEM predictions for
437 incoherent point sources are reliable.

438 4. 2.5-D BEM predictions

439 The 2.5-D BEM program was used to make predictions of attenuations
440 reduced by the nearly-enclosed barrier in order to identify its acoustic per-
441 formance in the surroundings. Run times with the complex geometry of
442 the nearly-enclosed barrier and railway vehicle simulation were excessive. In
443 order to reduce calculation times only the model with viaducts and nearly-
444 enclosed barriers but without rubber coverings(Figure 7(a1)) was calculated
445 for the whole frequency spectrum. Identically to the measurement, the cal-
446 culation was also completed without barriers(Figure 7(c1)) for attenuation
447 analysis.

448 4.1. *Rearrangement of source and receiver positions*

449 As we discussed in a previous article[21], based on the diffraction theory
450 the receiver positions need to be in all six significant acoustic areas: bright
451 zone, transition zone and shadow zone in the near field and far field, respec-
452 tively. The bright zone and transition zone for the nearly-enclosed barrier
453 were elongated and quite close to the source on the horizontal axis due to
454 the special shape of its top. The rest is therefore the shadow zone covering
455 most of the acoustic field. Considering that it is impossible to develop any
456 construction projects at the two former zones, our observation in this sec-
457 tion is focused on the performance at the shadow zone. Within this zone
458 the receiver positions were in the near field and far field separately. For the
459 frequency range of interest(50 Hz- 1000 Hz in the full scale) the boundary
460 between the near field and far field is located at around 14 meters away
461 from the source. Notice that further frequencies in Section 4 will be given

462 in the full scale. Consequently, by the grid-form method referred to in [21],
 463 predictions were made at receivers placed at the four receiver distances(5,
 464 10, 20 and 40 m from the centre of the track) on the horizontal axis and
 465 at the three receiver heights(1.5 m above, 1.5 m below and at the height of
 466 the track) on the vertical axis. Figure 14 illustrates these receiver positions.
 467 Given the large number of receiver positions, it was important to assign a
 468 name to each receiver. The name of each receiver begins with "M". The first
 469 number represents the column number which is smaller as the receiver gets
 470 closer to the source, whereas the second number represents the row number
 471 which is larger as the receiver gets closer to the ground. A symbol like "M1-"
 472 "M -1" which will be seen in later sections represents, for example, all the
 473 receivers in the first column or the first row, respectively.

Unlike only one point source simulated on the cross-section of the scale

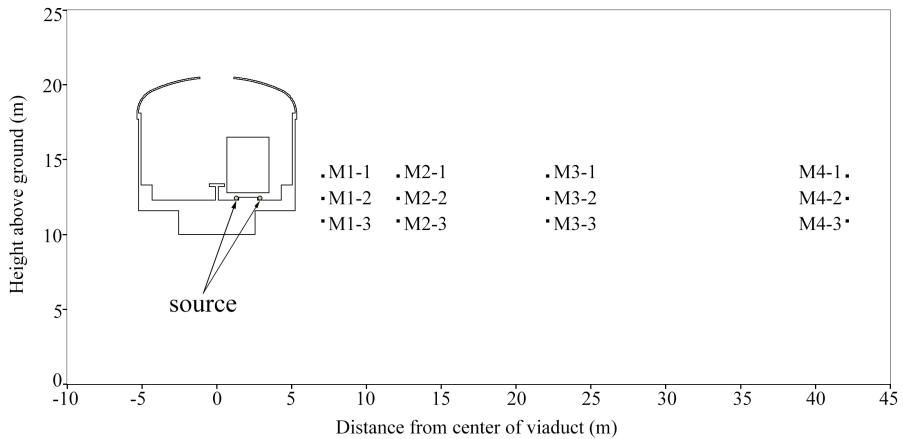


Figure 14: Source and receiver positions in the 2.5-D BEM calculation

474 model in the measurement, the noise sources were modelled as two incoher-
 475 ent point sources on the cross-section positioned at the approximate height
 476 of two rail-wheel interaction positions(represented by two dots in Figure 14).
 477 Note that the source to receiver distance discussed below represents the dis-
 478 tance horizontally away from centre of track(also the centre of two incoherent
 479 point sources on the cross-section). Identically to the previous calculation,
 480 the predictions for different numbers of sources(1, 4 and 12 incoherent point
 481 sources arrayed along the length of barrier) were made as well for all the re-
 482 ceivers mentioned above. Each distance perpendicular to the page between
 483 the source and receiver is also the same as that in the previous calculations.
 484

485 In the 2.5-D calculations, sound pressure was predicted for several in-
486 dividual frequencies with a linear spacing of 0.1 Hz per third octave band
487 ranging from 50 Hz to 1000 Hz. The energy for all the incoherent point
488 sources in the model was summed within each band yielding the third octave
489 band spectrum. Eventually the attenuation spectrum was calculated by the
490 logarithmic ratio of the energy obtained between the model without and with
491 the barrier.

492 *4.2. Near field*

493 Figure 15&16 show the predicted attenuations for the receivers in the
494 near field for different numbers of incoherent point sources. For the source to
495 receiver distance of 5 m there is a consistent pattern in the results obtained,
496 with the attenuation varying with the third-octave band for a given number
497 of sources, but to different degrees as observed in Figure 15. Among them
498 receiver M1-1 is the most greatly affected by changes in the band for a given
499 number of sources while there is the least effect for M1-3. And it can be seen
500 more obviously that the attenuation obtained with the highest receiver M1-1
501 is significantly greater than that obtained with the lowest receiver M1-3 for
502 all the third-octave bands of interest. That means the attenuation increases
503 with the increased height of receivers for all the cases examined in M1- and
504 the effect is very considerable.

505 However, with the increased number of sources, attenuation always de-
506 creases for a given receiver, and more importantly, it tends to fluctuate less.
507 Taking an example for receiver M1-1, the global maximum of attenuation for
508 one-point source is 41.61 dB at 630 Hz, while there are two local maximums,
509 31.94 dB and 28.56 dB at 250 Hz and 100 Hz, respectively. For the four-point
510 source the increase of attenuation from 630 Hz, to 1000 Hz is positive but
511 slow so that the global maximum is located at the maximum band of interest,
512 i.e. 41.83 dB at 1000 Hz. And obviously there is only one local maximum:
513 27.89 dB at 100 Hz. For the twelve-point source the attenuation increases
514 smoothly with the increased band and therefore it is difficult to find a local
515 maximum. Again, the global maximum is located at the maximum band of
516 interest, i.e. 39.34 dB at 1000 Hz.

517 The attenuation for the source to receiver distance of 5 meters in general
518 is higher than 13 dB for each band, and from 400 Hz to 1000 Hz it is even
519 higher than 20 dB. While for the source to receiver distance of 10 m the
520 attenuation is on average higher than 10 dB, and from 400 Hz to 1000 Hz it
521 is even higher than 15 dB. Figure 16 shows the attenuation achieved for the

522 source to barrier distance of 10 m for all configurations examined. Again, it
523 can be observed that there is a similar pattern in the results obtained with
524 the attenuation varying with the third-octave band for a given number of
525 source. However, unlike the predictions for receiver in M1- the attenuations
526 for the receiver in M2- are not greatly affected by changes in the height of
527 the receiver for a given third-octave band ranging from 50 Hz to 400 Hz,
528 although there is a small effect on attenuation from 500 Hz to 1000 Hz.

529 For the source to receiver distance of 10 m with the increased number
530 of source attenuation decreases again and tends to fluctuate less for a give
531 receiver. There is a similar trend for each receiver in M2- that the attenua-
532 tion ranging from 400 Hz to 1000 Hz firstly increases and then decreases for
533 one-point source, then increases slowly when the number increases to four,
534 and finally increases linearly for the twelve-point source. Because of this,
535 the associated frequency of the global maximum increases with the increased
536 number of sources, i.e. the global maximum for M2-1 is 25.33 dB, 28.13 dB
537 and 27.2 dB at 630 Hz, 800 Hz and 1000 Hz for the one-point, four-point
538 and twelve-point source respectively. On the other hand the global minimum
539 of attenuation for the one-point source for the receiver in M2- can be seen
540 clearly at 160 Hz with the value of approximately 6 dB, and it is the most
541 distinct trough in Figure 16. Nevertheless, this trough gradually disappears
542 for the four-point and twelve-point sources.

543 The following general conclusions can be drawn from the above: first,
544 the attenuation with an average of approximately 15 dB can be achieved
545 in the near field; secondly, the height effect of the receiver on attenuation is
546 significant for the source to receiver distance of 5 m while that for the source-
547 receiver distance of 10 m is almost invisible; thirdly, the increased number of
548 source can result in the smoother and lower attenuation.

549

550 4.3. Far field

551 Figure 17 &18 show the predicted attenuations for the receivers in the
552 far field for different numbers of incoherent point sources. For the source
553 to receiver distance of 20 m there is again a similar trend in the results
554 obtained, with the attenuation varying with the third-octave band for the
555 whole frequency range for a given number of sources(as observed in Figure
556 17). However, an opposite trend for the height effect of receivers can be
557 observed in M3- that attenuation decreases with the increased height of re-
558 ceivers for a given number of sources but the effect is very small.

559 With the increased number of sources, attenuation decreases for a given
560 receiver. A similar noticeable trough can be observed at 160 Hz in Figure 17
561 for one-point source, but it is surprising that it is a negative value and its
562 magnitude increases with decreased height for the receiver in M3- with the
563 lowest value of -2.46 dB. However, for all cases of the other two source types
564 the magnitudes of attenuations are always positive since the attenuation is
565 more stable with smaller fluctuations. For a given receiver there is also a
566 peak at 250 Hz for the one-point source but less obviously for the four-point
567 source, and it finally disappears for the twelve-point source. The attenuation
568 for the twelve-point source for the receiver in M3- fluctuates within a small
569 range of 6-13 dB ranging from 50 Hz to 400 Hz, and it increases slowly from
570 400 Hz to 1000 Hz.

571 The attenuation for the source to receiver distance of 20 m average is
572 lower than 20 dB for each band, while for the source to receiver distance
573 of 40 m the attenuation is on average lower than 10 dB. Figure 18 shows
574 the attenuation achieved for the source to barrier distance of 40 m for all
575 configurations examined. Again, it can be observed that there is a similar
576 pattern in the results obtained, with the attenuation varying with the third-
577 octave band for a given number of sources. And similar to those in Figure
578 17 attenuation decreases with the increased height of the receiver for a given
579 number of sources, but the effect is quite small.

580 Unlike the negative value of global minimum for all the receivers in M3-
581 for the one-point source, there is a negative attenuation as the global min-
582 imum only at 160 Hz for M4-2 for the one-point and the four-point source.
583 Apart from that, for the source to receiver distance of 40 m with increased
584 number of sources, attenuation for the receiver in M4- decreases and fluctu-
585 ates less again for a give receiver. For the global maximum, the associated
586 frequency is unchanged with the value of 50 Hz. And the magnitude firstly
587 increases and then decreases with increasing number of sources, i.e. for M4-
588 1 it is 17.80 dB, 18.58 dB and 16.10 dB for the one-point, four-point and
589 twelve-point source, respectively.

590 The following general conclusions can be drawn from the above: first,
591 the attenuation with an average of approximately 10 dB can be achieved in
592 the far field; secondly, the performance in the far field reduces with increasing
593 height of receivers but the effect is very small, in other words, the perfor-
594 mance is relatively unaffected by the height of receivers; thirdly, the increased
595 number of sources can result in the attenuation being much smoother and
596 lower, especially eliminating the negative value induced by the small number

597 of sources.

598 5. Discussion and conclusions

599 The 2.5-D BEM program developed for incoherent point source calcula-
600 tions was used to solve the practical problem of assessing the acoustic per-
601 formance outside a nearly-enclosed barrier with infinite length. The results
602 of a preliminary investigation calculated by the 2.5-D BEM program showed
603 that there were amounts of peaks in the frequency domain of sound pressure
604 in the surroundings of the nearly-enclosed barrier. With good agreement
605 between the sound pressure distributions at the peak frequencies and the
606 corresponding acoustic modes of the air cavity inside the barrier, a reason-
607 able explanation of these peaks was given that when the shape of the barrier
608 was nearly-enclosed, the acoustic resonance effect generated by the open air
609 cavity could result in extremely high levels at the resonance frequencies,
610 directly deteriorating the barrier performance. To suppress the resonance
611 effect the additional absorptive treatments on the inner surface of the barrier
612 is proposed for further research.

613 To validate the predictions a series of scale model measurements were
614 made since the scale modelling technique allowed the effect of the employed
615 material on the barrier performance to be more realistic. It was shown from
616 the comparison that there was a significant deviation between the measured
617 and predicted results for the nearly-enclosed barrier, but good agreement for
618 the double-straight barrier. Measured attenuations for the nearly-enclosed
619 barrier were obviously higher than those for the double-straight type in the
620 mid-frequency range, while at high frequencies, attenuations for the nearly-
621 enclosed barrier were almost the same as those for the double-straight type.
622 More importantly, the measured results for the nearly-enclosed barrier were
623 much lower than those predicted by the BEM, which may result from the
624 insufficient sound insulation of the PC panels.

625 Based on the sound insulation theory and the measured TLs in [19], the
626 transmission loss of the 5-mm-thick PC panels employed in the scale model
627 was estimated. The comparisons show that the predicted attenuations for
628 the nearly-enclosed type were quite close to the transmission loss of the PC
629 panels in the frequency range of interest. According to the calculation of
630 barrier attenuation in the form of energy transfer, the correction for sound
631 transmission could not be ignored. Therefore, the insufficient sound insula-
632 tion of the PC panels was identified to be the main cause of the differences

633 between the measured and predicted attenuations for the nearly-enclosed
634 barrier. As mentioned above, the PC panels, employed for the arched parts
635 in the full-scale prototype of the nearly-enclosed barrier in China, have a
636 thickness of only 6.5 mm, a little thicker than those employed in the scale
637 model in our test. Thus, the sound insulation of the PC panels in the actual
638 project are considered to be not sufficient as well. The need for transparent
639 material with better sound insulation and high flexibility was long ignored
640 and urgent for the arched parts, both in the scale model tests and the actual
641 projects.

642 With the help of 10-mm-thick rubber, a supplementary measurement was
643 developed for solving the difficulty. Fortunately, the predictions of one-third
644 octave band levels using the 2.5-D BEM program were shown to be com-
645 parable with the 1:20 scale measurements by fully coating all surfaces with
646 rubber so that confidence can be given in the BEM predictions for the whole
647 field. The compared results also reconfirmed the insulation problem of the
648 PC panels for the nearly-enclosed barrier. In addition, the predictions for the
649 four-point and twelve-point sources were shown to be comparable with the
650 measured results, which provides us the opportunity to discuss the number
651 effect of incoherent point sources.

652 Considering the complex sound field distribution caused by the specific
653 structure of a nearly-enclosed barrier, in order to understand thoroughly
654 the barrier performance, the receiver positions were rearranged according to
655 [21]. The rearrangement approach based on the diffraction theory was used
656 to estimate the performance of the sound barrier in each area with different
657 acoustic features.

658 As expected, the attenuation of the nearly-enclosed barrier averaged around
659 15 dB in the near field and around 10 dB in the far field. This indicates that
660 the nearly-enclosed type has a more effective and efficient performance on the
661 premise that all the boundaries are acoustically rigid. This kind of barrier
662 with high attenuation designed by the modification of shape requires the em-
663 ployed material with sufficiently high sound insulation property. Otherwise
664 the design will be largely failed and not economical for the practical use.

665 It was also shown that the attenuation decreased with increasing source-
666 receiver distance, while it increased with increasing height of receivers only
667 in the column which was the closest to the source in our study. For the
668 other three source-receiver distances the height effect of receiver was almost
669 negligible. The number effect of incoherent point sources was also taken into
670 account for modelling railway traffic noise. Apparently, the increased num-

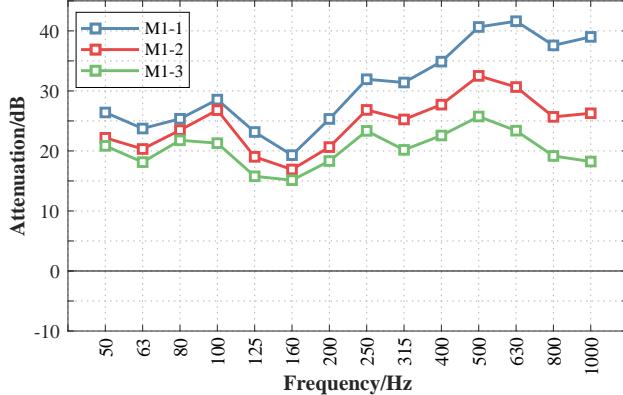
ber of source can result in much smoother and lower attenuations for all the areas, especially eliminating the negative value induced by the small number of sources. In addition, the resonance effect referred to previously can be the reasonable explanation of the negative values of the attenuations in the far field.

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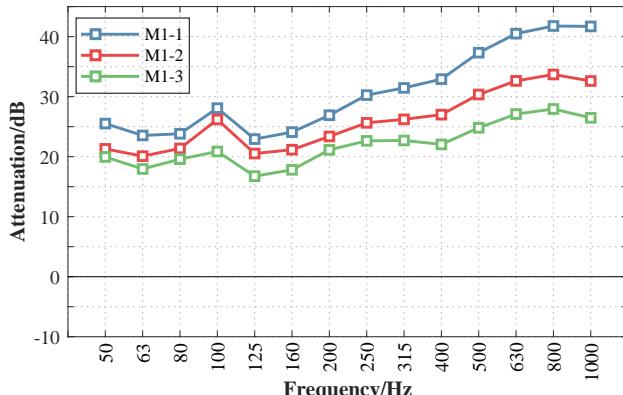
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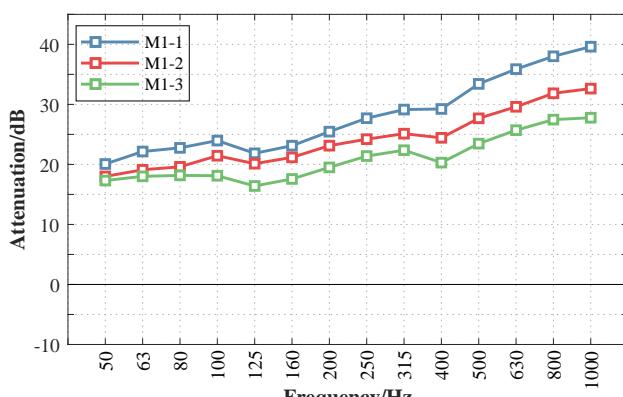
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(a) one-point source

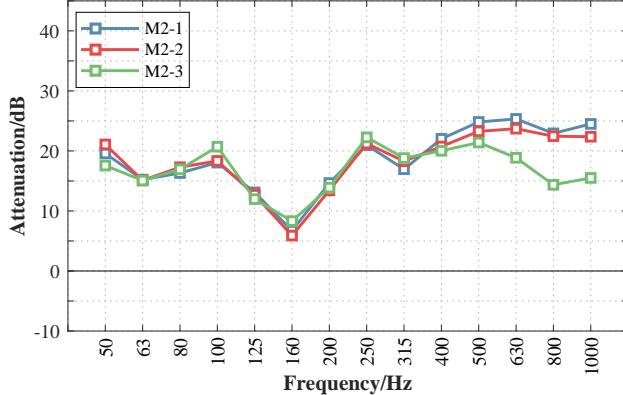


(b) four-point source

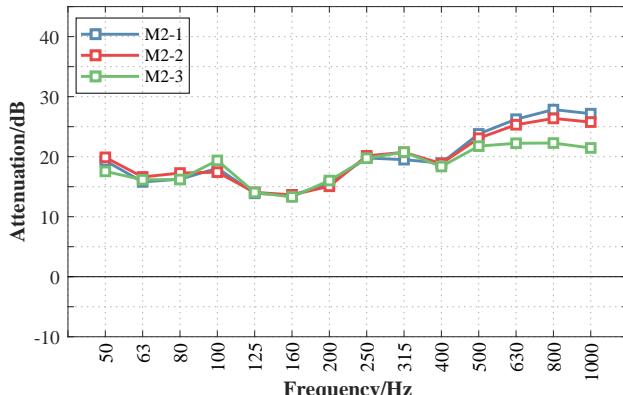


(c) twelve-point source

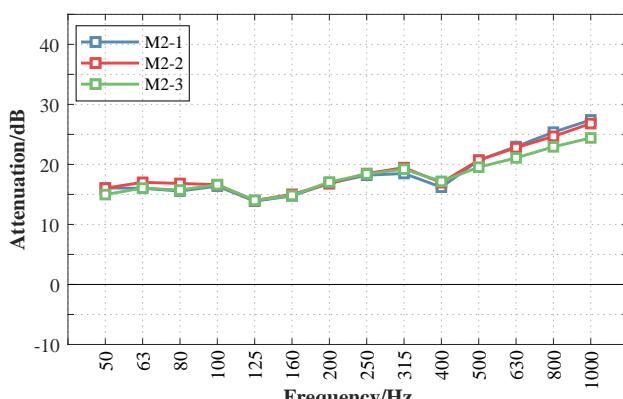
Figure 15: Predicted attenuations for the source to receiver distance of 5 meters



(a) one-point source

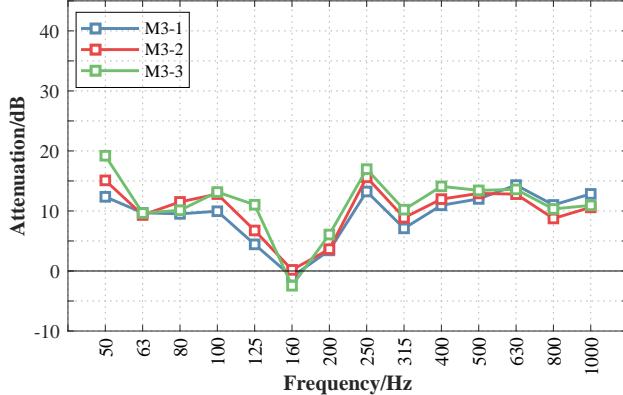


(b) four-point source

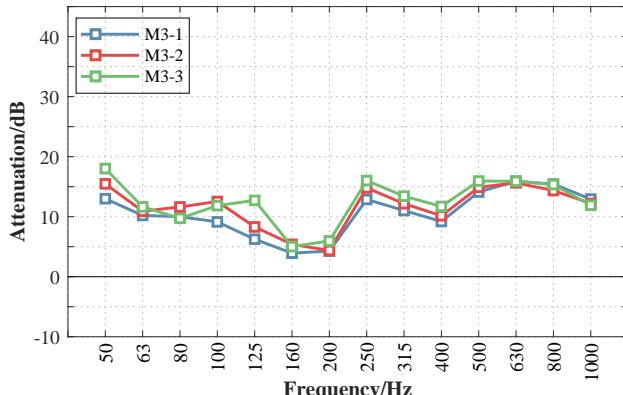


(c) twelve-point source

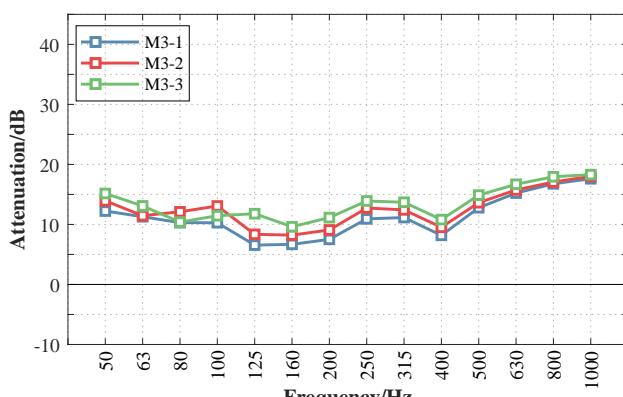
Figure 16: Predicted attenuations for the source to receiver distance of 10 meters



(a) one-point source

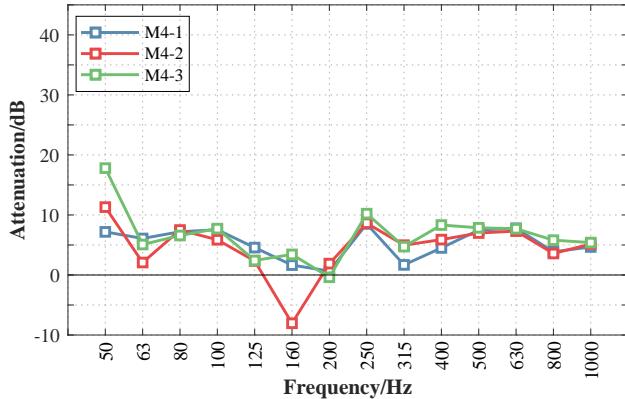


(b) four-point source

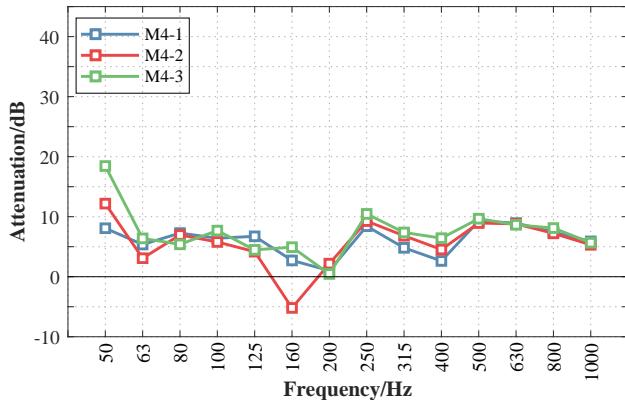


(c) twelve-point source

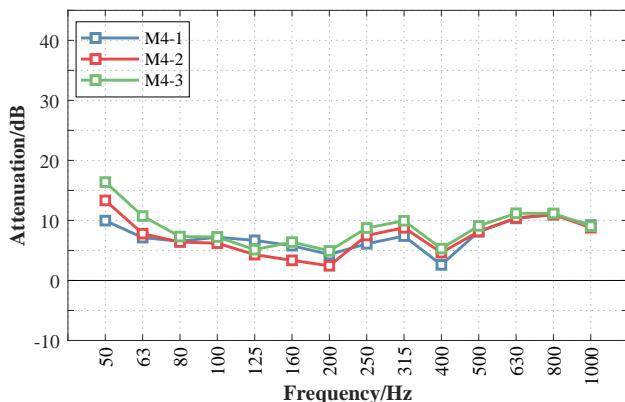
Figure 17: Predicted attenuations for the source to receiver distance of 20 meters



(a) one-point source



(b) four-point source



(c) twelve-point source

Figure 18: Predicted attenuations for the source to receiver distance of 40 meters