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Qiutong Li, Denis Duhamel, Honore Yin, Yanyun Luo. Comparative Analysis of Different Types of Sources on the Performance of Rigid Noise Barriers on Rigid Ground Using Analytical Formulae, a 2.5-D BEM Method and Scale Modelling Tests. *Acta Acustica united with Acustica*, 2019, pp.987-999. 10.3813/AAA.919379 . hal-02892324

**HAL Id: hal-02892324**

<https://enpc.hal.science/hal-02892324v1>

Submitted on 7 Jul 2020

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# Comparative analysis of different types of sources on the performance of rigid noise barriers on rigid ground using analytical formulae, a 2.5-D BEM method and scale modelling tests

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## 1 Summary

With the aim of a perfect source model to simulate railway traffic noise within a shorter computational time, this paper compares coherent line, incoherent point and incoherent line sources on the performance of barriers by using an analytical solution, a 2.5-D BEM method and scale modelling tests. The comparison between the analytical solutions and the 2.5-D BEM prediction results shows that the BEM calculations for a coherent line source can be used to approximately show the barrier attenuation spectrum for a one-point source and the single-number rating for an incoherent line source when the barrier is straight on the ground. Then, validations with scale modelling tests were performed outdoors under controlled conditions. The results obtained by using several loudspeakers radiating incoherent sounds simultaneously show good agreement with the 2.5-D BEM prediction results for the one-point source and incoherent point sources, not only for a simple barrier on the ground but also for a double-straight barrier on a viaduct. Based on these agreements, the frequency and longitudinal distance dependences on the barrier attenuation for incoherent point sources are discussed to understand the barrier attenuation spectrum for the incoherent line source.

## 1 Introduction

Noise barriers are widely used in traffic systems to reduce exposure to traffic noise in surrounding residential and commercial areas. The railway noise source is typically assumed to be an incoherent line source, but to predict the barrier performance within an acceptable computational time, a coherent line source (2-D BEM) or a one-point source facing the receiver (3-D BEM) is always considered as the alternative in the numerical calculations. Compared with the computational cost of 2-D BEM calculations, the cost for 3-D calculations significantly increases due to the sophisticated matrix computations. Furthermore, be-

cause the element size must be less than one-sixth the sound wavelength, the cost for higher frequency calculations is considerably high, even in two dimensions. The calculation time also depends on other parameters, such as the frequency range of interest and the absorptive surface treatments. The long calculation time is the main problem for solving 3-D BEM models, especially for barriers with complicated tops, and the calculations are often conducted using a 2-D BEM approach[1, 2, 3, 4](with coherent line sources). In the early years, D.C. Hothersall et al.[1] discussed the 2-D BEM model of T-profile and associated noise barriers based on the results obtained from experimental modelling and field measurements. They found that the predicted results were not applicable to the incoherent line source, but the relative performances of different barrier shapes would be similar. I. Takashi et al.[2] studied the performance of road traffic noise barriers with various shapes and surface conditions using only a 2-D BEM method. When studying the efficiency of low-height noise reduction devices applied on the roadside, M. Baulac et al.[3] carried out 1:10 scale model measurements to confirm the effectiveness. They found good agreement between the 2D theoretical results and 3D scale model measurements. Moreover, F. Koussa et al.[4] studied the acoustic performance of conventional and low-height gabion noise barriers using a 2-D BEM model and scale model measurements. The agreement of the results between the two methods was satisfactory.

However, using 2-D BEM models for researching railway/road traffic noise was found to be inappropriate because the results obtained for these cases were noticeably different. P. Jean et al.[5] emphasised the importance of source type on the assessment of noise barriers. Using the Fourier-like transformation proposed by [6], they found that the barrier attenuation was overestimated if coherent line sources were considered, whereas the efficiency of a cap on the top of a straight barrier was underestimated with coherent line sources. Later, with the help of a BEM program that they compiled, their team[7] obtained the real

82 performance of a T-shaped absorbing cap with road  
 83 traffic noise conditions on the ground. They found  
 84 that the results of cap efficiency for a coherent line  
 85 source were different from those for an incoherent line  
 86 source. For the highest frequencies, the efficiency was  
 87 proportional to the path difference. They also found  
 88 the slantwise propagation effects on the barrier at-  
 89 tenuation for a point source when the source-receiver  
 90 distance was not perpendicular to the barrier with a  
 91 simple analytical formula. However, to date, there  
 92 has been little research that can clarify the slantwise  
 93 effects of the distance between the source and receiver  
 94 along the barrier  $|z_s - z_r|$  (in the third direction per-  
 95 pendicular to the cross-section plane, it will be given  
 96 as "longitudinal distance" for clarity) on the perfor-  
 97 mance of barriers with arbitrary shapes.

98 To reduce the computational time in 3-D BEM cal-  
 99 culations, D. Duhamel[6, 8] proposed a 2.5-D method  
 100 in which the results obtained for coherent line sources  
 101 can be transformed via Fourier-like transformations  
 102 to those corresponding to incoherent point or line  
 103 sources. Using this method, many articles have pre-  
 104 dicted the performance of acoustic screens for inco-  
 105 herent point (or line) sources in different applications.  
 106 Forssen et al.[9] compared the results predicted by a  
 107 2.5-D BEM method and the results obtained from an  
 108 in situ measurement, which showed reasonable agree-  
 109 ment. S. Sakamoto et al.[10] and M. Hiroe et al.[11]  
 110 employed a Fourier-like transformation in a 2-D finite-  
 111 difference time-domain analysis to study the noise  
 112 shielding effect of eaves/louvres attached on build-  
 113 ing façades and the propagation of sound from sur-  
 114 face railways. The calculation method was validated  
 115 by the experimental results. Based on the above suc-  
 116 cessful experiences, the present paper continues to use  
 117 this 2.5-D method to compare the results of different  
 118 types of sources to predict the performance of urban  
 119 railway noise barriers.

120 The predictions must be validated by the measure-  
 121 ment results obtained from outdoor in situ[9, 7] or  
 122 scaled laboratory tests[3, 10, 11, 4]. In situ mea-  
 123 surements may be time-consuming, and it is difficult  
 124 to find a real environment as simple as the numeri-  
 125 cal model(rigid barrier, rigid flat ground, no reflect-  
 126 ing obstacles, etc.), even if background noise can be  
 127 rejected using controlled signals(such as ESS, MLS)  
 128 and the intrinsic characteristics of noise barriers can  
 129 be measured in situ with a given reproducibility[12].  
 130 However, performing large-scale measurements re-  
 131 quires extremely large anechoic laboratories that are  
 132 not easy to build and run. Hence, only a few  
 133 studies[13, 14, 15, 16] related to in situ measurements  
 134 have been published.

135 Because of the difficulties in conducting in situ mea-  
 136 surements discussed above, a measurement method  
 137 in which small-scale model tests are used instead  
 138 offers a reliable alternative for predicting perfor-  
 139 mance. Many articles[17, 18, 19] have used the scale

140 modelling method to understand the propagation of  
 141 road/railway traffic noise to the surrounding envi-  
 142 ronment, and the scaled measurement method has  
 143 been widely employed in the study of noise barrier  
 144 performance[20, 21, 22, 23, 24, 25]. Based on the in-  
 145 variance of the speed of sound in air, the performance  
 146 of real barriers in the field can be imitated by the  
 147 results of scale models, which is possible when the  
 148 measured frequency range is increased by the same  
 149 scale factor to the typical range of interest for the  
 150 urban railway traffic noise. The scaled approach is  
 151 perfectly suited for our research because we focus on  
 152 comparing different source types to evaluate the per-  
 153 formance of a simple barrier on the ground and a  
 154 double-straight barrier on a viaduct, which are as-  
 155 sumed to be rigid throughout. In addition, it is known  
 156 that the impedance of surfaces must be scaled with  
 157 complicated computations, not as that of an acoustic  
 158 rigid surface, which is infinite. Such surfaces with ab-  
 159 sorbent treatments are not considered in this paper.

160 Various sound sources, such as air-jet and electro-  
 161 acoustic sources, laser-generated acoustic pulses and  
 162 electric sparks, have been used during the measure-  
 163 ment process, depending on the scale-modelling ap-  
 164 plication. G.R. Watt et al.[20] used an air-jet whis-  
 165 tle activated by an air supply at 10 atmospheres to  
 166 simulate an omni-directional point source. Among  
 167 the different source types that are able to provide  
 168 these characteristics, spark discharge in air is an in-  
 169 teresting solution. Many studies have presented the  
 170 characteristics of the spark discharge, which can be  
 171 regarded as an adjustable acoustic source for scale  
 172 model measurements[19, 26, 23, 3]. For researching  
 173 the propagation of explosions and sonic booms con-  
 174 veniently in the laboratory, Q. Qin et al.[27] inves-  
 175 tigated the characteristics of acoustical shock waves  
 176 associated with a focused pulsed laser beam. Aiming  
 177 at modelling incoherent point sources, our approach is  
 178 to use scaled outdoor experiments and several point  
 179 sound sources. The sound radiated simultaneously  
 180 by several miniature loudspeakers with uncorrelated  
 181 white noises is easily considered to be that of inco-  
 182 herent point sources. This approach can validate the  
 183 prediction results not only for the one-point source  
 184 but also for the incoherent point sources, thus pro-  
 185 viding a new avenue for predicting the results for an  
 186 incoherent line source.

187 The main purpose of the present work is to deter-  
 188 mine whether the assumption of coherent line sources  
 189 is acceptable for predicting the performance of rigid  
 190 noise barriers on rigid ground. Section 2 preliminar-  
 191 ily examines the effects of different source types on  
 192 a simple straight barrier on the rigid ground, with  
 193 three configurations of source and receiver positions,  
 194 using a 2.5-D BEM method and an analytical solu-  
 195 tion. This analysis can provide a preliminary expla-  
 196 nation for the comparison of different source types. In  
 197 Section 3, a scale model technique is developed with

the help of miniature loudspeakers, and a set of scaled measurements is presented with a short description of the set-up; the results and comparisons between the measured and predicted results are then discussed. Section 4 is devoted to the frequency dependence and longitudinal distance dependence of the barrier attenuation for the incoherent point sources, which better characterises the barrier performance in the case of incoherent point or line sources. Some conclusions are then presented in Section 5.

## 2 Comparison with an analytical solution

In this section, our objective is to seek a much closer approximation to the real solution for the sound field due to an incoherent line source in the vicinity of a sound barrier. For simplicity, the time-dependent factor of  $e^{-i\omega t}$  is understood and omitted from the whole computation process. Suppose that the distance between the source and receiver is  $R$ , and therefore, the acoustic field for a free space is  $e^{ikR}/4\pi R$  assuming the customary source term of  $-\delta(x - x_s)$ [28]. In [28], K.M. Li sorted many different analytical models for calculating the sound diffraction by a thin infinite barrier. Among these models, we selected one of the frequently used exact solutions, which was developed by MacDonald[29], for comparison with the results predicted by the BEM approach for a one-point source. The expression of the sound field in the shadow zone was recast by Bowman and Senior[30] in the cylindrical polar system due to the original idea solved using the spherical polar coordinate, given as follows:

$$p_D = \frac{ik \operatorname{sgn}(\zeta_1)}{4\pi} \int_{|\zeta_1|}^{\infty} \frac{H_1^{(1)}(kR_1 + s^2)}{\sqrt{s^2 + 2kR_1}} ds + \frac{ik \operatorname{sgn}(\zeta_2)}{4\pi} \int_{|\zeta_2|}^{\infty} \frac{H_1^{(1)}(kR_2 + s^2)}{\sqrt{s^2 + 2kR_2}} ds \quad (1)$$

where  $i$  is the imaginary number,  $k$  is the wave number of the incident wave, and  $H_1^{(1)}$  is the Hankel function of the first kind.  $\zeta_1$  and  $\zeta_2$  are the limits of the contour integrals, which are determined by

$$\zeta_{1,2} = \operatorname{sgn}(|\theta_s - \theta_r| - \pi) \sqrt{k(R' - R_{1,2})} \quad (2)$$

where  $R_1$  and  $R_2$  are determined by

$$R_{1,2} = \sqrt{r_s^2 + r_r^2 - 2r_s r_r \cos(\theta_s \mp \theta_r) + (y_s - y_r)^2} \quad (3)$$

Moreover, the shortest source-edge-receiver path can be determined by

$$R' = \sqrt{(r_s + r_r)^2 + (y_s - y_r)^2} \quad (4)$$

where  $(r_s, \theta_s, y_s)$  and  $(r_r, \theta_r, y_r)$  are the cylindrical coordinates of the source and receiver, respectively.

Note the lack of consideration of the sound reflection induced by the ground because the solution was deduced starting from the assumption of a semi-infinite screen. Generally, sound reflection by the rigid ground or a rigid viaduct is tacitly included in the performance of a sound barrier for road/rail traffic systems. Based on the pertinent theory, the sound reflecting from the surface of the rigid ground or a rigid viaduct can be considered to radiate in terms of an image source located symmetrically with the infinite plane. Likewise, the effect on the receiver side can be described as an image receiver. Consequently, the total sound field influenced by the barrier's diffraction together with the ground's reflection is the summation of four diffracted paths when the surface is fully reflective. This symmetrical method is introduced in the post process of the calculation to allow the solution to approximate that for the case where the noise barrier is on the rigid ground in outdoor situations but is not exactly the same because the barrier is semi-infinite in the analysis, whereas it is of finite height in reality.

In the present study, using a 2.5-D BEM approach to model the sound field generated from coherent line and incoherent point and line sources, the existing program SAMRAY developed by Duhamel[6, 8] was introduced. The solution for a coherent line source is generally known as a 2-D BEM result that can easily be calculated. Then, via a Fourier-type integration, the solution for a one-point source can possibly be obtained from a series of 2-D results when all the boundaries are assumed to be acoustically rigid[6]. The calculations for incoherent line sources can also be made by 2-D solutions, which have been discussed in [6]. Note that the solution for an incoherent line source is represented by the density of acoustic potential energy because the source is modelled as a line of uncorrelated point sources perpendicular to the cross-section of the barrier. Based on these discussions, the existing program allows calculating the radiation and the diffraction of sound fields for general 2-D and 2.5-D structures for coherent line, point and incoherent line sources. Considering the totally reflective ground effect, the comparison of predictions calculated by SAMRAY with the analytical solution is described here for three cases:

1. A source and a receiver located on the totally reflective ground.
2. A source located on the ground, and a receiver 1.0 m above the totally reflective ground.
3. A source 1.0 m above the ground, and a receiver 1.5 m above the totally reflective ground.

Figure 1 shows diagrams of the three configurations and the 2-D coordinates of the source and the receiver. The straight barrier was assumed to be totally reflective as well, with a height of 1.85m and a thickness of 0.17m. To compare the analytical solutions for a

294 one-point source with the BEM results for a coherent  
 295 line source, a one-point source and an incoherent  
 296 line source, the barrier attenuation  $Att_b$ , which is the  
 297 sound pressure difference between the site without a  
 298 barrier and the site with a barrier was introduced and  
 299 is given by

$$Att_b(f) = 10 \log \frac{p_{wo}^2(f)}{p_w^2(f)} \quad (5)$$

300 where  $p_{wo}(f)$  and  $p_w(f)$  denote the sound pressure at  
 301 the given receiver position in the case of the mod-  
 302 els without and with a barrier, respectively. Figure  
 303 2 shows the barrier attenuation as a function of  
 304 frequency calculated by each analytical or numerical  
 305 model for each case. Each model was run at 0.1 Hz  
 306 from 44.7 Hz to 112 Hz and at 1 Hz from 113 Hz  
 307 to 5623 Hz. In Figure 2, each dotted curve repre-  
 308 sents the barrier attenuations in the frequency spec-  
 309 trum whereas the solid curve of the same colour cor-  
 310 responds to the results in one-third-octave bands from  
 311 50 Hz to 5000 Hz. Thus, the latter appears to be  
 312 much smoother than the former. In case 1 (Figure  
 313 1(a)), both the source and the receiver are located on  
 314 the ground such that there is no need to consider the  
 315 reflection effect in terms of the ground. Without the  
 316 ground effect, Figure 2(a) only shows the component  
 317 diffracted by the barrier top. As shown in the figure,  
 318 the increase in the barrier attenuation is proportional  
 319 to the rise in the logarithm of frequency, regardless of  
 320 the source type. However, in case 2, considering the  
 321 ground effect on the side of the receiver, the barrier  
 322 attenuation varies regularly with frequency for the co-  
 323 herent line source and the one-point source. The pe-  
 324 riod of the variation depends on the path difference  
 325 between the direct way of sound transmission and the  
 326 reflecting way, which is governed by the height of the  
 327 receiver above the ground. Furthermore, as shown in  
 328 Figure 2(c), with the source and the receiver at dif-  
 329 ferent heights above the ground, the barrier attenua-  
 330 tion varies irregularly like a combination of two dif-  
 331 ferent periodic variations.

332 Compared with the results for the coherent line  
 333 source and the one-point source, those for the inco-  
 334 herent line source (yellow curves) are distinctly dif-  
 335 ferent. The sound pressure levels for the incoherent  
 336 line source were calculated by the energy density for  
 337 an infinite line of incoherent point sources such that  
 338 the corresponding barrier attenuation at each frequency  
 339 could be considered as the averaged results for the  
 340 uncorrelated point sources with different longitudinal  
 341 distances. Section 4.2 will elaborate the effect of the  
 342 longitudinal distance on the attenuation of barriers.  
 343 Hence, the trend for the incoherent line source shown  
 344 in Figure 2 is in accordance with the average charac-  
 345 teristic that the barrier attenuation increases with fre-  
 346 quency much more slowly than the other results. For  
 347 this reason, the curve of the one-third-octave spec-  
 348 trum can be used to more precisely describe the fre-

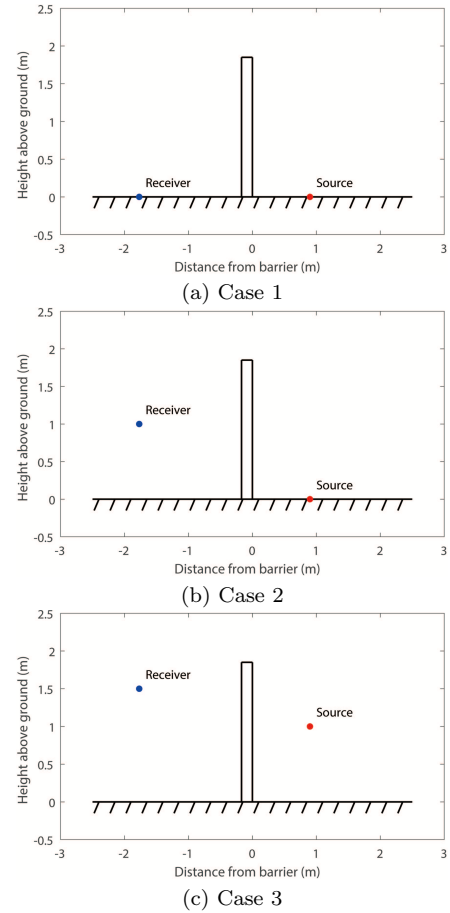


Figure 1: Cross-sections of the three configurations  
 calculated in the comparison with the analytical solu-  
 tion

349 frequency spectrum for the incoherent line source. When  
 350 considering incoherent line sources in further studies,  
 351 the estimation results calculated for central frequen-  
 352 cies of one-third octave bands are sufficient to show  
 353 an accurate spectrum. Another conclusion in [6] can  
 354 be observed in Figure 2: the barrier attenuations for  
 355 the coherent line source in each subfigure have good  
 356 agreement with that for the one-point source in the  
 357 spectrum, while in the one-third-octave band analysis,  
 358 the barrier attenuations for the one-point source are  
 359 slightly higher than those for the coherent line source.  
 360 Because the result for the one-point source is gener-  
 361 ated by the Fourier-like transformation of that for the  
 362 coherent line source, it is not surprising to obtain this  
 363 conclusion. For this reason, when considering a one-  
 364 point source in further studies, the calculations for a  
 365 coherent line source can serve as the alternative to  
 366 reduce the computational time. In addition, it is also  
 367 indicated that the totally reflective ground effect had  
 368 little influence on the comparison of these sources.

369 The red curves presented in Figure 2 represent  
 370 the analytical solutions for the one-point source used  
 371 to validate the numerical predictions calculated by  
 372 SAMRAY. Clearly, the analytical solutions have good

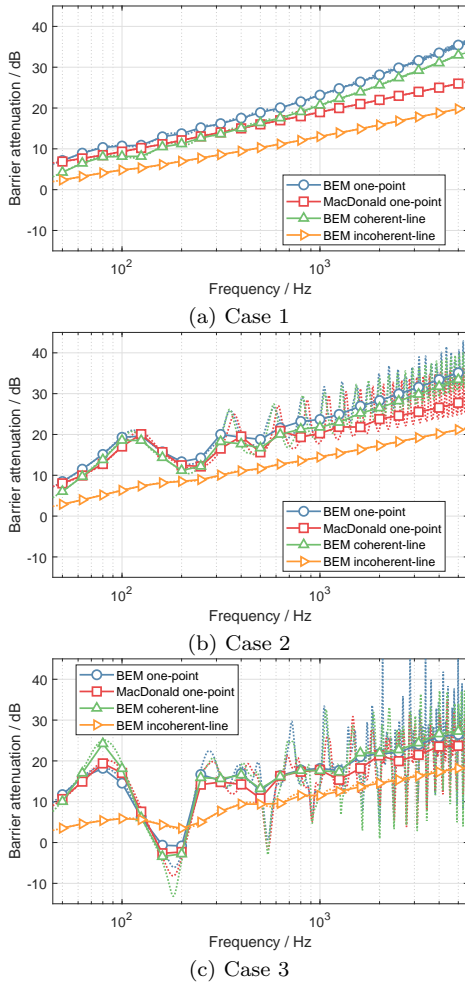


Figure 2: Barrier attenuation spectra for the three configurations calculated in the comparison

373 agreement with those predicted by the BEM at low frequencies. However, at mid and high frequencies, the analytical solution becomes much lower, and the variation period becomes much longer. The reason for this result lies in the assumption of the barrier thickness. At the beginning of the analytical calculation, the barrier was assumed to be thin with a thickness of zero. However, in the calculation process of the 2.5-D BEM modelling, the thickness could be modelled equivalently to that of the actual barrier. Figure 3 compares the analytical solution for case 1 with the 2.5-D BEM results predicted for the barrier with different thicknesses. It is clear that the differences between the analytical solution and the BEM results are small at low frequencies, free from the change in thickness. However, with an increase in frequency, the difference is considerably increasing, which is caused by the increased thickness. Thus, it was validated that the results predicted by SAMRAY must be closer to the actual values due to the consideration of the barrier thickness, particularly for the results at mid and high frequencies.

395 Except for the frequency spectrum, we al-

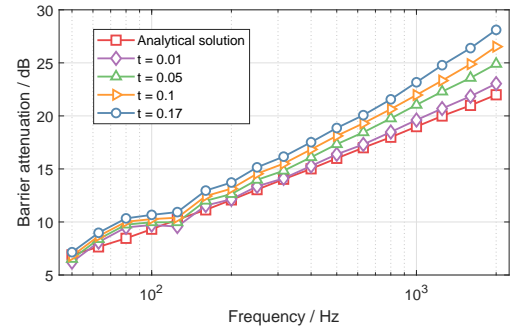


Figure 3: The analytical solution for case 1 compared with the 2.5-D BEM results of the barrier with different thicknesses (units: m)

396 ways use a single-number rating within the frequency range of interest to analyze the barrier performance. The single-number rating is often called "insertion loss" (IL), which can be given by

$$\text{IL} = 10 \log \frac{\int_{f_{\min}}^{f_{\max}} p_{\text{wo}}^2(f) df}{\int_{f_{\min}}^{f_{\max}} p_{\text{w}}^2(f) df} \quad (6)$$

400 where  $f_{\min}$  and  $f_{\max}$  are the lower and upper limits of the frequency range, respectively.

401 According to the norm ISO 10847:1997[31], the frequency range for the railway traffic noise is recommended to range from 50 Hz to 5000 Hz. To compare the single-number ratings for the one-point source between the two calculation methods, we find from Table 1 that the results predicted by the 2.5-D BEM were 2-3 dB higher than those obtained from the analytical solutions, which were the results of the assumed thin barriers in the analytical model. Notably, by comparing the insertion losses predicted by the 2.5-D BEM program for different source types, the results for the coherent line source are in good agreement with those for the incoherent line source but are much lower than those predicted for the one-point source. This result is why many studies considered the sound field radiated by a coherent line source as that for an incoherent line source, although the results observed in the frequency spectrum are completely contrary to each other. Hence, it is indicated that the insertion loss for the coherent line source can be used to estimate the value for the incoherent line source to reduce the computational time.

### 3 Comparison with scale modelling tests

425 With the assumption of the actual thicknesses of barriers, the 2.5-D BEM prediction results must be much closer to the actual values compared with the analytical solutions. However, the predictions for the three

Table 1: Insertion losses for three configurations for different types of sources (frequency range: 50-5000 Hz)

IL / dB	Analytical solution		Predicted results by BEM	
	One-point	One-point	Coherent line	Incoherent line
Case 1	19.7	22.9	11.7	14.2
Case 2	21.3	24.1	14.8	15.2
Case 3	17.7	19.7	13.4	13.0

431 cases need to be validated using the scale modelling  
 432 method. In addition to the three cases for a one-point  
 433 source discussed in Section 2, a case with a double-  
 434 straight barrier installed on a box girder viaduct(case  
 435 4) was introduced to more realistically study the rail-  
 436 way noise barrier system. Nevertheless, it remains  
 437 quite difficult to model the incoherent line source that  
 438 is commonly used to more closely reflect the traffic  
 439 noise. Because the incoherent line source can be con-  
 440 sidered an infinite line of uncorrelated point sources  
 441 perpendicular to the cross-section, several incoherent  
 442 point sources were introduced into the test and per-  
 443 formed for cases 3 and 4. Consequently, the scale  
 444 model measurement with several point sources was  
 445 made to not only validate the 2.5-D BEM prediction  
 446 results for the one-point source but also for the in-  
 447 coherent point sources. Due to the size limitation of  
 448 the experiment site, the scales of cases 1-3 were de-  
 449 termined to be 1:10, whereas that of case 4 was 1:20.

### 450 3.1 Test setup

451 The tests for the one-point source were performed in  
 452 the four abovementioned cases. For the first three,  
 453 the solid plane barrier remained unchanged at 18.5  
 454 cm high and 1.7 cm wide. The site was an open field  
 455 on unknown asphalt. To ensure good acoustic reflec-  
 456 tion to simulate rigid surface conditions, a wood plank  
 457 with an area of  $1.2 \times 1.8m^2$  was placed on the asphalt  
 458 (as shown in Figure 4), which was sufficiently large to  
 459 offer an approximate rigid ground in our scale model  
 460 test. Figure 4 also shows that a layer of sand was  
 461 inserted to fill the air gap between the plank and the  
 462 asphalt to eliminate the influence of vibration of the  
 463 panel and the air cavity resonance effect under the  
 464 plank surface.

465 For case 4, the barriers and the viaducts were  
 466 made of 9-mm-thick wood panels. The scale model  
 467 was based on a real prototype and is shown in Figure  
 468 5(a), with a length of 6 m. Double-straight barriers  
 469 with a height of 2.4 cm were located on the box girder  
 470 viaduct, which was 50 cm above the ground supported  
 471 by discontinuous piers, with the gap between each two  
 472 being 1 m. The receiver was positioned towards the  
 473 centre of the model where there was no pier. Figure

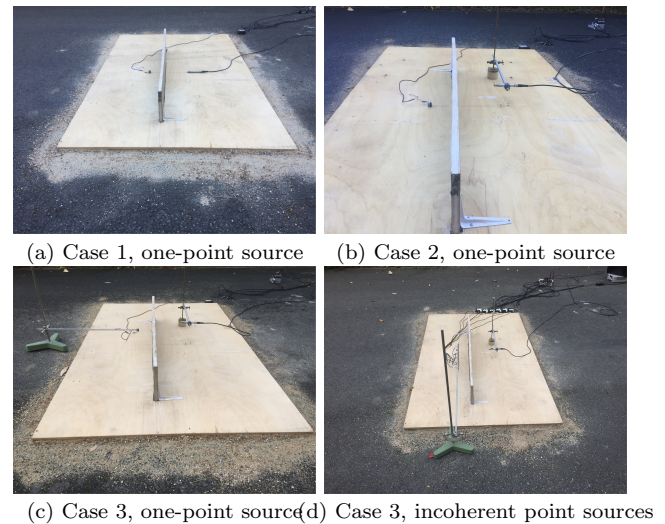


Figure 4: The scenes of the scale model tests for the former three cases

5(b) shows the cross-section of the real model. Due  
 to the large vehicle structure, secondary reflections  
 pose a problem, and thus, the train itself had to be  
 taken into account in the scale modelling tests. The  
 T-shape part in the centre of the viaduct was designed  
 as a safe passage. Since the viaduct was the closest  
 reflective surface to the source and was elevated above  
 the ground, the acoustical characteristic of the ground  
 seemed a lot less important. Hence, there was no need  
 to place the wood plank on the asphalt in case 4.

To evaluate the performance of the barriers, it was  
 necessary to prepare the configurations without bar-  
 riers. For the first three cases only, the straight bar-  
 rier was removed, and for case 4, the double-straight  
 barrier was removed(as shown in Figure 5(c)). The  
 positions of the loudspeakers and microphones were  
 unchanged. To describe the positions of the sources  
 and receivers for each case, the horizontal distance to  
 the surface of the barrier was denoted by  $x$ , the ver-  
 tical distance to the ground was denoted by  $y$ , and  
 the longitudinal distance to the microphone along the  
 barrier was denoted by  $z$ . Figures 1 and 5 show the  
 coordinates for each real model while Table 2 illus-  
 trates the coordinates for both the real and the scale  
 models. The tests for a one-point source, where the  
 perpendicular from the source to the receiver meets  
 the barrier( $z_r = z_s = 0$ ), were performed first. Then,  
 the tests for incoherent point sources were conducted  
 with the number of sources increased for cases 3 and  
 4, with other coordinates of loudspeakers and micro-  
 phones remaining constant. Note that in each case,  
 the height of the receiver was less than that of the  
 barrier, which is a result of the need to keep the re-  
 ceiver well within the shadow zone.

The BEM model assumes omni-directional inco-  
 herent point sources, which were achieved in prac-  
 tice by using miniature loudspeakers (produced by  
 RS PRO, RS stock code: 1176047), activated by am-

Table 2: Positions of the loudspeakers and microphones in three coordinates(m)

(a) For a one-point source													
Real model	Microphone		Loudspeaker		Scale model	Microphone		Loudspeaker					
	$x_r$	$y_r$	$x_r$	$y_r$		$x_r$	$y_r$	$x_r$	$y_r$				
Case 1	1.6	0.0	0.9	0.0	Case 1	0.16	0.00	0.09	0.00				
Case 2	1.6	1.0	0.9	1.0	Case 2	0.16	0.10	0.09	0.10				
Case 3	1.6	1.5	0.9	1.0	Case 3	0.16	0.15	0.09	0.10				
Case 4	2.0	16.1	2.42	12.4	Case 4	0.10	0.805	0.121	0.62				

(b) For incoherent point sources													
Real model	Loudspeaker												
	Num	$z_s$											
Case 3	1	0.00											
	3	-0.35 0.00 0.35											
	12	-2.10	-1.75	-1.40	-1.05	-0.70	-0.35	0.00	0.35	0.70	1.05	1.40	1.75
Case 4	1	0.00											
	4	-19.78 -7.18 0.00 12.60											
	12	-59.34	46.74	-39.56	-26.96	-19.78	-7.18	0.00	12.60	19.78	32.38	39.56	52.16

Scale model	Loudspeaker												
	Num	$z_s$											
Case 3	1	0.0											
	3	-3.5 0.0 3.5											
	12	-21.0	-17.5	-14.0	-10.5	-7.0	-3.5	0.0	3.5	7.0	10.5	14.0	17.5
Case 4	1	0.0											
	4	-98.9 -35.9 0.0 63.0											
	12	-296.7	-233.7	-197.8	-134.8	-98.9	-35.9	0.0	63.0	98.9	161.9	197.8	260.8

512 plifiers (Viston, AMP 2.2 LN, Art. No. 7102) and  
 513 a power supply (EA-PS 2042-10B). The sound ra-  
 514 diated from the speakers was generated by a signal  
 515 output module (NI 9263) installed in a NI DAQ sys-  
 516 tem (CDAQ-9174). The effective maximum frequency  
 517 of the miniature loudspeaker was up to 20 kHz in  
 518 the one-third octave band. Together with the fre-  
 519 quency range of railway traffic noise recommended in  
 520 ISO 10847:1997(50-5000 Hz), the measured frequency  
 521 ranges in cases 1-3 were determined to be 500 Hz to  
 522 20 kHz, and that in case 4 was 1000 Hz to 20 kHz.  
 523 Hence, the measured results can simulate a 50-2000  
 524 Hz emission for cases 1-3 and a 50-1000 Hz emission  
 525 for case 4 in the real-size problem.

526 During the measurement, one or more loudspeak-  
 527 ers simultaneously emitted random white noise in the  
 528 same one-third octave band for 10 seconds from the  
 529 signal output module. Meanwhile, sound pressure sig-  
 530 nals were received by microphones and transferred  
 531 to the signal input module. The ten-second random  
 532 white noise was based on continuous integrated sound  
 533 pressure levels, so the barrier end effects had to be  
 534 limited. To limit the end effects, the receiver was po-  
 535 sitioned towards the centre of the barrier, and both  
 536 barrier ends were filled with mineral wool to absorb  
 537 the sound diffracted by the ends. Each test was re-  
 538 peated five times.

539 All the tests were conducted in the same place. The

540 tests of each case with and without the barrier were  
 541 carried successively at the site, lasting for approxi-  
 542 mately one hour in total. In the duration of the test  
 543 for each configuration, the effect of humidity and tem-  
 544 perature on air absorption of high frequencies was  
 545 considered unchanged. Since the attenuation of the  
 546 straight or double-straight barrier that was of our in-  
 547 terest was the difference in level between the sites with  
 548 and without barriers, the effect of humidity and tem-  
 549 perature could be ignored. Nevertheless, the temper-  
 550 ature during the tests was measured, as presented in  
 551 Table 3.

Table 3: Temperature of tests( $^{\circ}$ C)

	Number of loudspeakers	Configurations	
		Without a barrier	With a barrier
Case 1	1	22.1	21.8
Case 2	1	21.9	22.0
	1	22.3	22.2
Case 3	3	22.2	22.2
	12	22.3	22.5
Case 4	1	17.8	17.6
	4	17.7	17.5
	12	17.8	17.9



was given by

$$Att_{b,\text{sum}}(f) = 10 \log \frac{\sum_{i=1}^N p_{w0}^2(f, z_{si})}{\sum_{i=1}^N p_w^2(f, z_{si})} \quad (7)$$

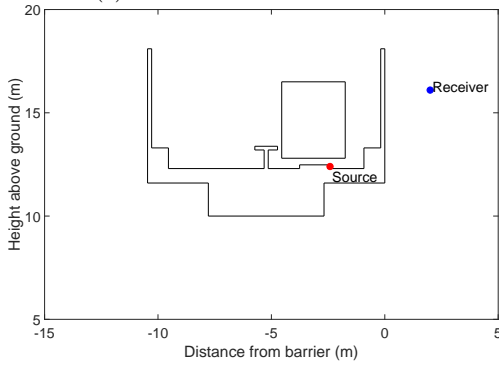
where  $p_{w0}(f, z_{si})$  and  $p_w(f, z_{si})$  denote the sound pressure at the given receiver position radiated from the source located at  $z_{si}$  in the case of the models without and with the barrier, respectively.  $N$  denotes the number of incoherent point sources. The barrier attenuations at one-third-octave band frequencies from 50 Hz to 2000 Hz were calculated to be compared for the first three tested cases, whereas those from 50 Hz to 1000 Hz were calculated for case 4.

For the one-point source that was perpendicular to the receiver, Figure 6 shows plots of the measured and predicted barrier attenuations by the one-third-octave band spectrum for all four cases. The frequency range of the measured spectrum was adjusted in the analysis to be identical to the predicted results. Hence, the frequencies will be given in full scale for clarity. As expected, there are good agreements between the measured results obtained in the scale model tests and those predicted by the 2.5-D BEM approach. However, the measured barrier attenuations are slightly higher than those predicted by the BEM, particularly for high frequencies. This result was considered to be normal and permissible due to the sound absorption of the wood panels and the non-idealised point source in the scale test.

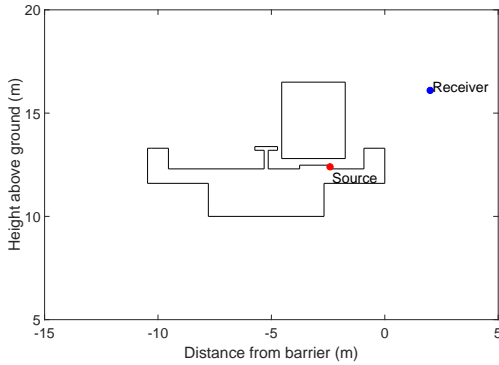
In Figure 7, the results for different numbers of



(a) The scene of the scale model



(b) The cross-section with a barrier in the BEM calculation



(c) The cross-section without a barrier in the BEM calculation

Figure 5: Configurations of case 4

### 3.2 Test results compared to the 2.5-D BEM predictions

Predictions were performed for the straight and double-straight barriers using the 2.5-D BEM program SAMRAY. The one-point source in the model was placed in exactly the same position as for the scale model tests. The number of sources defined was initially one for modelling the one-point source, followed by adding sources to reach three or four and finally reaching twelve sources. The barrier attenuation of the one-point source for each case was calculated by using Eq (5). By contrast, to yield the results by the combined effect of different incoherent point sources, the barrier attenuation for incoherent point sources

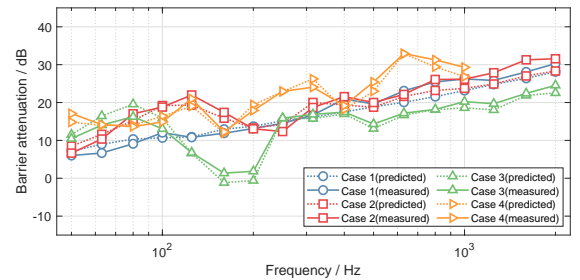


Figure 6: Measured and predicted barrier attenuations for the one-point source

loudspeakers in cases 3 and 4 are compared. Here, the simultaneous sound sources were lined up along the length of the barrier, only differing by the longitudinal distance. As shown in Figure 7, the measured result for each case in general has a good agreement with the prediction, which indicates that by using the 2.5-D BEM approach, the predicted barrier attenuations for incoherent point sources are accurate as well. Looking into the details, there are discrepancies at the peaks (80 Hz and 200 Hz) for case 3, which can be caused by the warping tendency of the wood plank on the ground. It is also clear that all the curves

605 in Figure 7(a) are too close to distinguish from each  
 606 other. This result means that the number of incoher-  
 607 ent point sources has little effect on the attenuation  
 608 of the straight barrier on the ground. Nevertheless,  
 609 there is no proof that the number effect can be ignored  
 610 when referring to the barrier attenuation for incoher-  
 611 ent point sources.

612 For the double-straight barrier on the viaduct, as  
 613 shown in Figure 7(b), it is easy to understand that  
 614 the growth of the barrier attenuation seriously fluctu-  
 615 ates with frequency for the one-point source. It is  
 616 surprising that the barrier attenuation mostly tends  
 617 to gradually increase as the number of incoherent  
 618 point sources increased to four. When the number  
 619 of sources increased to twelve, the barrier attenuation  
 620 has a slight decrease at each frequency band compared  
 with those for four-point sources.

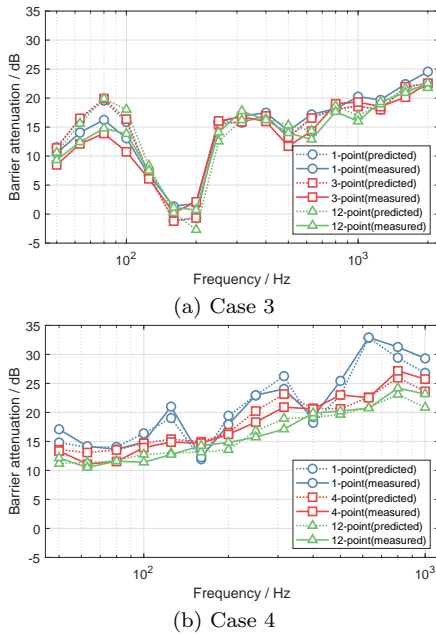


Figure 7: Measured and predicted barrier attenuations for incoherent point sources

## 4 Discussion

623 The attenuation of a barrier varies with the sound  
 624 frequency. Moreover, the barrier attenuation also  
 625 changes with the number of incoherent point sources  
 626 because the longitudinal distances for incoherent  
 627 point sources are diverse. Therefore, the attenuation  
 628 of a barrier can be affected by the longitudinal dis-  
 629 tance. Based on the two cases from which the results  
 630 were validated by the scale model tests, this section  
 631 will discuss the frequency dependence and the longitu-  
 632 dinal distance dependence of the barrier attenuation.

### 4.1 Frequency dependence

633 The frequency dependence for case 3 was discussed in  
 634 section 2. The barrier attenuation varies as a com-  
 635 bination of two different periodic variations in the  
 636 frequency spectrum, and the period is mainly depen-  
 637 dent on the path difference between the direction way  
 638 and the reflection way governed by the height of the  
 639 source and the receiver above the ground. For case  
 640 4, Figure 8 shows the predictions of the barrier at-  
 641 tenuations in the spectrum of 50-2000 Hz. Unlike the  
 642 results for the simple straight barrier on the totally  
 643 reflective ground, the barrier attenuation for the one-  
 644 point source violently fluctuates regardless of sound  
 645 frequency, as does that for the coherent line source.  
 646 As discussed in [32], a reflecting barrier fixed on the  
 647 source side could result in the deterioration of bar-  
 648 rier performance due to the acoustic resonance effect.  
 649 Hence, the resonance effect can be a reasonable ex-  
 650 planation of the valleys illustrated in Figure 8. Nev-  
 651 ertheless, there are indistinct valleys at the resonant  
 652 frequencies in the configuration with four-point and  
 653 twelve-point sources and even no visible valleys in the  
 654 configuration with the incoherent line source. Consid-  
 655 ering that the resonance effect did not disappear upon  
 656 changing the longitudinal distance, these smoother  
 657 trends must have a relationship with the calculated  
 658 barrier attenuation for incoherent point sources.

659 From Eq (7), it appears that the barrier attenua-  
 660 tion, the ratio of the whole sound power of the  
 661 model without and with the barrier, is the average  
 662 of the results for all the uncorrelated point sources.  
 663 Then, our focus is shifted to the frequency spectrum  
 664 for each incoherent point source. Figure 8(c) shows  
 665 the one-third-octave spectrum for part of twelve point  
 666 sources in case 4, where  $|z_{si} - z_r|$  denotes the longi-  
 667 tudinal distance for the  $i$ th point source. As shown,  
 668 with a change in the longitudinal distance, the bar-  
 669 rier attenuation spectrum performed significantly dif-  
 670 ferently along the sound frequency. When the whole  
 671 sound power for such calculated point sources was ob-  
 672 tained, the averaged characteristics must result in the  
 673 decrease of peaks and valleys in the spectrum. The  
 674 decreasing trend is more evident as the number of  
 675 sources or the longitudinal distance increases. As-  
 676 suming that the incoherent line source is a line of such  
 677 incoherent point sources with an extremely small dis-  
 678 tance between each two sources along the line that is  
 679 infinitely long perpendicular to the cross-section, the  
 680 averaged characteristics lead to the smoothest barrier  
 681 attenuation, as shown by the purple curve in Figure  
 682 8(b). However, for the coherent line source, there is al-  
 683 most no change in the frequency spectrum in terms of  
 684 the different longitudinal distances in the assumption,  
 685 and therefore, the frequency spectrum corresponding  
 686 to the coherent line source performed almost the same  
 687 as that for the one-point source. In Figure 8(b), there  
 688 is good agreement for the one-third-octave spectrum  
 689

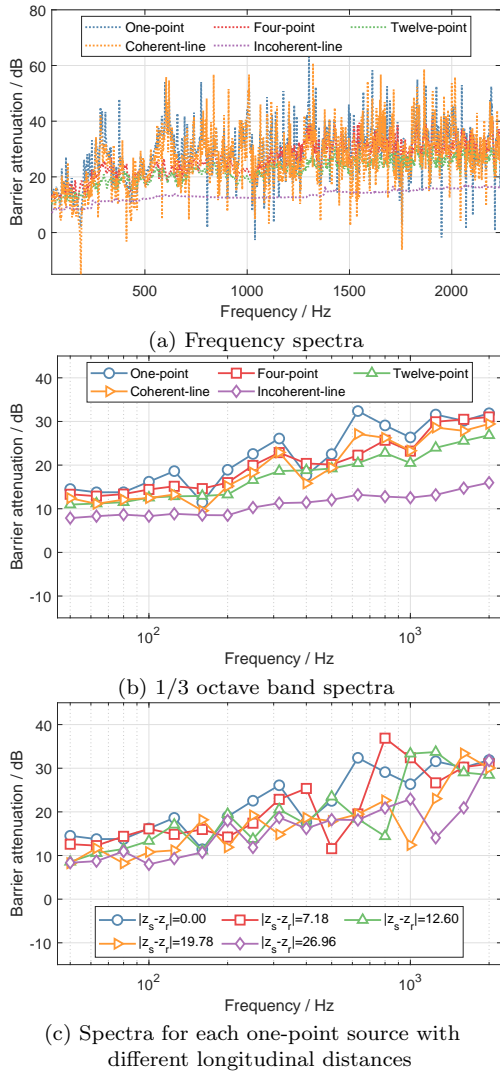


Figure 8: The spectra of barrier attenuations for case 4 calculated by the 2.5-D BEM approach

690 between the one-point source and the coherent line  
 691 source, which provides further evidence that the calcu-  
 692 lation in the frequency domain for a coherent line  
 693 source can be considered an alternative to analyse the  
 694 barrier performance with a one-point source. In addi-  
 695 tion, the spectrum for the coherent line source is  
 696 slightly lower than that for a one-point source, which  
 697 is due to the averaged characteristics of the coherent  
 698 line source.

699 The single-number ratings for different numbers of  
 700 incoherent point sources are illustrated in Table 4.  
 701 With different numbers of incoherent point sources,  
 702 the insertion loss for case 3 is essentially unchanged.  
 703 By contrast, the insertion loss in case 4 decreases con-  
 704 siderably with the number of sources and becomes  
 705 closer to that for the incoherent line source, which  
 706 is identical to the comparison in the frequency spec-  
 707 trum. The different trends for cases 3 and 4 could be  
 708 due to the longitudinal distance dependence, which  
 709 will be detailed in Section 4.2. Another comparison of

710 the insertion loss is between the one-point source and  
 711 the coherent line source. The former is higher than  
 712 the latter at approximately 6 dB for both cases, al-  
 713 though their frequency spectra were almost the same,  
 714 as mentioned above. Then, the single ratings for the  
 715 coherent line source and the incoherent line source  
 716 manifest similarly, with the former being higher than  
 717 the latter by only 2 dB, embodying the "line" intrinsic  
 718 feature of the assumption of the coherent line source.  
 719 In conclusion, the results for a coherent line source  
 720 have presented not only a frequency spectrum that is  
 721 approximate to that for the one-point source but also  
 722 a single-number rating that is approximate to that for  
 723 the incoherent line source.

## 724 4.2 Longitudinal distance dependence

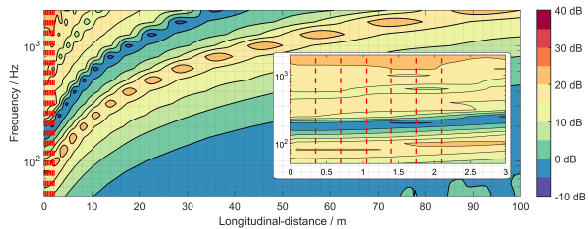
725 As explained above, the change in longitudinal dis-  
 726 tance of the point source results in significant differ-  
 727 ences in the barrier attenuation spectrum. Because  
 728 the incoherent line source was considered a line of  
 729 such point sources, according to Eq (7), the average  
 730 of such a spectrum for each distance can be the re-  
 731 sulting spectrum for the incoherent line source, which  
 732 is notable because of its smoothness and slow growth  
 733 with frequency. Hence, studying the longitudinal dis-  
 734 tance dependence is of great importance. To clarify  
 735 the relationship between the longitudinal distance of  
 736 the point source and the barrier attenuation, the spec-  
 737 tra of the barrier attenuation in both cases 3 and 4  
 738 for each incoherent point source with different lon-  
 739 gitudinal distances were calculated. Figure 9 shows  
 740 the predicted barrier attenuation spectra with filled  
 741 contours when the longitudinal distance is within 100  
 742 meters. The x axis denotes the longitudinal distance,  
 743 and the y axis denotes the sound frequency on a log  
 744 scale. For comparison, the contours for both cases 3  
 745 and 4 use the same colour map.

746 In Figure 9(a), increasing the longitudinal dis-  
 747 tance generally results in the shift of the spectrum  
 748 to higher frequencies, approximately following a lin-  
 749 ear relationship. Then, the spectrum for every non-  
 750 zero longitudinal distance is therefore divided into two  
 751 components by frequencies: the relatively lower values  
 752 at low frequencies and the spectrum for the previous  
 753 distance at mid and high frequencies(e.g., for the lon-  
 754 gitudinal distance of 40 m, the barrier attenuations at  
 755 200-2000 Hz have the same trend as those in the whole  
 756 frequency range for 10 m, whereas the barrier atten-  
 757 uations below 200 Hz are lower). In addition, there  
 758 are closed contours periodically in the relationship be-  
 759 tween the spectrum and longitudinal distance(e.g., or-  
 760 ange closed contours), which cannot be identified in  
 761 the spectrum only for the one-point source or the co-  
 762 herent line source. With the help of the longitudinal  
 763 distance dependence, the barrier attenuation for the  
 764 incoherent line source can be presented thoroughly.

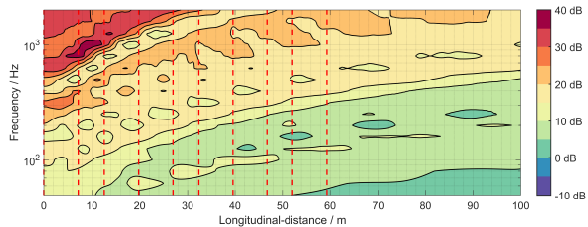
765 The filled contour in Figure 9(b) is excessively com-

Table 4: Single ratings for different types of sources

IL / dB		Predicted results by the 2.5-D BEM				
Case 3	One-point	Three-point	Twelve-point	Coherent line	Incoherent line	
(50-5000 Hz)	19.7	19.9	19.8	13.4	13.0	
Case 4	One-point	Four-point	Twelve-point	Coherent line	Incoherent line	
(50-2000 Hz)	20.5	19.4	17.3	13.7	11.8	



(a) Case 3, the straight barrier on the ground, source-receiver distance perpendicular to the barrier: 2.67 m



(b) Case 4, the double-straight barrier on the viaduct, source-receiver distance perpendicular to the barrier: 4.415 m

Figure 9: The relationships between the longitudinal distance and the barrier attenuation spectrum

766 plicated mainly due to the acoustic resonance effect  
 767 caused by the double-straight barrier, generally with  
 768 much higher levels than those in Figure 9(a). At first  
 769 glance, the contour of 35 dB occurs at frequencies  
 770 from 800 Hz to 1250 Hz at distances of 5 m to 12 m  
 771 but not at a distance of zero, which is another finding  
 772 highlighting the importance of the longitudinal distance  
 773 for modelling incoherent point or line sources. Secondly,  
 774 identical to Figure 9(a), the spectrum shifts to higher  
 775 frequencies with increasing longitudinal distance. However,  
 776 the relationship cannot be approximate to the linearity,  
 777 and at some frequencies, it can be described with logarithmic  
 778 curves. The spectrum for the longer distance decreases at  
 779 low frequencies and remains at high levels at mid and high  
 780 frequencies. At a distance of 100 m, the spectrum still  
 781 appears higher than 10 dB at frequencies above 500 Hz,  
 782 which means that even the longitudinal distance is approx-  
 783 imately twenty-five times the source-receiver distance  
 784 perpendicular to the barrier and that the sound pressure  
 785 level at the receiver position is still greatly affected by  
 786 the barrier attenuation. In view of this result, when con-  
 787 sidering modelling of the incoherent line source, the fre-  
 788 quency spectrum for the coherent line or one-point source  
 789 cannot be an acceptable alternative.  
 790  
 791

792 In general, the longitudinal distance dependence for  
 793 a specific case must be analysed specifically due to the  
 794 significant difference between these two contours.

795 To explain the different effects of the number of the  
 796 incoherent point sources on the barrier attenuation  
 797 results between cases 3 and 4, the barrier attenuation  
 798 spectra for those incoherent point sources tested in the  
 799 scale experiments are marked by red dashed lines, as  
 800 shown in Figure 9. Because the red lines are densely  
 801 packed together for case 3, the part including all the  
 802 red lines is zoomed in and shown by a small picture  
 803 in Figure 9 (a). It can be seen that the barrier atten-  
 804 uation spectra in case 3 for each tested point source  
 805 are almost the same because the distances between  
 806 each point source along the barrier in case 3 are too  
 807 short to cover the entire area of the longitudinal dis-  
 808 tance dependence. For this reason, the calculations  
 809 for case 3 must result in the identity of the results  
 810 for one-point, three-point and twelve-point sources,  
 811 which is in accordance with the experimental results  
 812 shown in Figure 8(a) and Table 4. However, in case 4,  
 813 the more complex relationship between the distance  
 814 and the barrier attenuation spectrum causes the re-  
 815 sults for each point source to be more diverse than  
 816 those in other point studies. Consequently, the results  
 817 for each tested point source are considerably different,  
 818 as marked by red dashed lines shown in Figure 8(b). As  
 819 a result, as the number of incoherent point sources  
 820 increases, the spectrum for case 4 clearly changes. In  
 821 conclusion, the study on the longitudinal distance de-  
 822 pendence of barrier attenuation through 2.5-D BEM  
 823 modelling provides a reasonable explanation for the  
 824 experimental results.

## 5 Conclusion

825  
 826 In this paper, the attenuations of a rigid straight bar-  
 827 rier on the rigid ground and a double-straight bar-  
 828 rier on a rigid viaduct generated from different types  
 829 of sources have been investigated. A first compari-  
 830 son has been achieved by the analytical solution pro-  
 831 posed by MacDonald and the 2.5-D BEM predictions  
 832 by SAMRAY, able to obtain the similarities and dif-  
 833 ferences among the one-point source, coherent line  
 834 source and incoherent line source. Then, a measure-  
 835 ment procedure using several loudspeakers radiating  
 836 incoherent sounds simultaneously with two scale mod-  
 837 els has been presented to verify the 2.5-D BEM cal-  
 838 culations for different numbers of incoherent point

839 sources. From the 2.5-D BEM results, it has been possible to determine the frequency and longitudinal distance dependence of the barrier attenuation spectrum for incoherent point sources to introduce it into modelling the spectrum for an incoherent line source. In addition, the single-number rating for the frequency range of interest has also been analysed for all configurations.

847 The following conclusions can be drawn from the predictions and measurements:

- 849 1. The solutions of the analytical formulae show good agreement with the 2.5-D BEM calculations (for a one-point source) both in the spectrum and the single-number rating. This result validates the 2.5-D BEM calculation program, but to calculate the barrier attenuation for a one-point source, it is better to use the BEM approach rather than the analytical formulae due to the concretization of the barrier thickness. With increasing simple barrier thickness, the barrier attenuation increases more obviously at higher frequencies.
- 861 2. As expected, there is good agreement of the barrier attenuation spectrum at a given receiver position between a one-point source (2.5-D BEM) and the corresponding coherent line source (2-D BEM). Hence, from the perspective of saving time, the 2-D BEM method can be directly used to estimate the attenuation spectrum of the barrier for a one-point source. However, the single-number rating for a coherent line source (2-D BEM) seriously underestimates that for a one-point source, the former being lower than the latter by 6-10 dB, which cannot be directly used for the estimation of a one-point source.
- 874 3. With the characteristics of "line", the single-number rating results for a coherent line source are close to the calculations for an incoherent line source (within an error of 3 dB), although the barrier attenuation spectra between them are noticeably different. Hence, the single-number rating for a coherent line source (2-D BEM) can be used to estimate that for an incoherent line source.
- 883 4. By using several loudspeakers radiating incoherent sounds simultaneously, the scale modelling test results show good agreements with the 2.5-D BEM calculations for both the configurations of the straight barrier on the ground and the double-straight barrier on a viaduct. The presented scale modelling test method can be used for the certification of incoherent point sources in a laboratory and in situ.
- 892 5. The presented scale modelling test results validate the 2.5-D BEM calculations for incoherent

894 point sources of a simple model, as well as a complex model that is typical of urban railway transit configurations. Hence, the BEM approach generalised to predict the attenuation of rigid barriers on rigid ground for an incoherent line source can be reliable, even for a more sophisticated rigid barrier model on rigid ground.

- 901 6. The results of the double-straight barrier obtained for a coherent line source or a one-point source facing the receiver fluctuate violently, mainly depending on the acoustic resonance induced by the multiple reflections between the two parallel barriers.
- 907 7. An increased number of incoherent point sources can result in the barrier attenuation spectrum becoming smoother and lower and lead to a clear decrease in single-number ratings for the whole frequency range of interest. Nevertheless, the barrier attenuation still increases with frequency with a lower growth rate.
- 914 8. Using the 2.5-D BEM method, the source-receiver direction was introduced. Unlike the invariance under translation in the distance of the spectrum for a coherent line source, the spectrum for an incoherent point source shifts to higher frequencies with increasing longitudinal distance, and the barrier attenuations at low frequencies generally decrease with increasing longitudinal distance.
- 923 9. The smoother and lower barrier attenuation spectra for the incoherent line source can be explained by the dependence on the longitudinal distance of the incoherent point source. As the incoherent line source is assumed to be a line of incoherent point sources, the barrier attenuation spectrum for the incoherent line source can be solved by the ratio of the whole sound energy integral of incoherent point sources along the line for the model without and with a barrier. With the average characteristics, the spectrum becomes smoother and lower.
- 935 10. In this way, the testing of a new barrier employed on an urban railway transit can be performed by means of scale model measurements for incoherent point sources, as well as 2.5-D BEM calculations. However, the barrier performance in reality under the metro operating conditions should be obtained through 2.5-D BEM calculations for incoherent line sources. For a preliminary crude investigation, the single-number rating obtained for a coherent line source can be used to predict the real performance of the barrier.

## Acknowledgement

This work was supported in part by the National Natural Science Foundations of China (Nos. 51708422, 51678446, 51408434). The authors would like to acknowledge many people who were involved in this work. Extra thanks go to Christophe BERNARD, Daniel CINTRA, Gwendal CUMUNEL, Zhehao ZHU and Yichun LIU for their additional valuable help. The authors also wish to thank the China Scholarship Council and Ecole Nationale des Ponts et Chaussées for providing the financial assistance to LI Qitong necessary to pursue her Ph. D. in France.

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