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Validation of Noise Barrier Insertion Loss Simulation in Reducing Road Traffic Noise by Site Measurement Data

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ABSTRACT

A noise barrier serves as a method to control noise pollution resulting from road traffic, particularly prevalent in rural areas near heavy traffic routes such as highways. This study focuses on simulating the sound Insertion Loss (IL) of existing noise barriers designed to mitigate road traffic noise around school areas. The primary goal is to assess the precision of the Finite Element Modeling (FEM) program. Utilizing the finite element analysis software, COMSOL, the study models the noise barrier and its surroundings in two-dimensional acoustic radiation problem based on on-site dimensions and parameters. By examining the often-neglected aspect of noise leakage and its impact on noise reduction, the research aims to provide specific guidance for urban planners and architects to optimize noise mitigation in various urban settings. The study reveals a strong agreement between the simulated IL and on-site measurements, with a minimal difference ranging from 0.4 dB to 1.1 dBA on average. Additionally, the research suggests potential improvements to simulation accuracy through adjustments in aperture sizes. The findings demonstrate that finite element simulation can be a valuable tool for designers to assess the effectiveness of noise barriers before construction begins.

Keywords:
Noise barrier; Insertion Loss; FEA Simulation

1. Introduction

The continuous expansion of transportation infrastructure and the growing demand for efficient road networks have led to the ubiquitous presence of highways in both urban and suburban areas. While the construction and implementation of roads have undoubtedly improved accessibility and connectivity, it is imperative to recognize the consequential and enduring environmental issue—specifically, noise pollution [1-4]. Extensive literature documents the adverse effects of highway noise on neighboring communities, encompassing sleep disruption, diminished cognitive abilities, and increased susceptibility to cardiovascular ailments [5]. Consequently, integrating noise

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abatement strategies, such as noise barriers, has become a crucial aspect in the planning and development of these transportation corridors [6-9].

Noise barriers, also known as sound barriers or noise walls, have evolved into essential components of modern transportation infrastructure (Figure 1). Originating in the 20th century, these barriers address the increasing concerns about noise generated by vehicles in proximity to highways and heavily trafficked roads. The evolution of noise barriers involves advancements in both materials and design, utilizing materials like concrete, metal, earth berm, and vegetation to create customized solutions that effectively reduce noise while aesthetically integrating with the surroundings [10,11]. The efficiency of noise barriers is influenced by factors such as barrier height, distance from the road, and geometry, with Finite Element Modeling (FEM) commonly employed for forecasting and assessing noise reduction [12]. Beyond their utilitarian role, noise barriers have gained attention for their aesthetic and environmental attributes, prompting the development of visually appealing designs and environmentally conscious solutions that seamlessly blend into urban environments. Ongoing research into community well-being and ecological consequences suggests that noise barriers will continue to advance, with the emergence of "smart" barriers incorporating cutting-edge technologies [13].

Fig. 1. Panel (top), Berm (bottom left), and Vegetation (bottom right) are the type of noise barriers

The study introduces the COMSOL Multiphysics FEM program, specifically designed for simulating acoustic problems. This program allows users to model sound propagation, diffraction, reflection, and absorption using the Acoustics Module. For studying the acoustical behavior of barriers, the software enables the construction of intricate geometries, definition of material properties, specification of boundary conditions, and execution of multiphysics simulations. The precision and reliability of simulations depend on user input parameters, model assumptions, and boundary conditions [14,15].

The research aims to address a fundamental question: how accurately does FEM represent the efficacy of highway noise barriers? In the realm of noise barrier design and evaluation, faith in the accuracy and reliability of simulation models is vital. The study emphasizes the importance of validating FEM predictions against empirical data to establish its reliability in guiding noise mitigation strategies. This research contributes significantly to the broader academic discourse on sustainable urban development and transportation planning by tackling the persistent issue of noise pollution associated with highway infrastructure [16-19]. It underscores the importance of rigorous scientific validation in the development and implementation of highway noise barriers, with the goal of fostering quieter and more harmonious coexistence between highways and neighboring communities [20]. The study addresses a critical gap in the field of noise barrier design and effectiveness by investigating the impact of noise leaks on noise reduction—an often-overlooked parameter in existing studies. The research aims to provide precise guidelines for urban planners and architects striving to optimize noise mitigation in diverse urban contexts. The primary objective is to comprehensively evaluate how different noise barrier configurations impact noise reduction while validating the accuracy of simulations using FEM against on-site measured data. Through these objectives, the study seeks to contribute to the advancement of noise barrier design and urban planning, promoting quieter and more livable urban environments.

2. Methodology

In this study, the simulated Insertion Loss data were compared to the existing experimental data obtained by Haron *et al.,* (2019). The experimental study had been undertaken at a primary school location afflicted by noise pollution from the Skudai-Johor Bahru motorway. The 2-dimensional models had been used to simulate the noise barrier's acoustic performance by using commercial FEA software, COMSOL. This simulation's main goals are to aid in data collecting for later validation and to give a visual depiction of the conditions of the experiment. To assess the simulation's correctness, it is essential that the simulation's conclusion closely resembles or substantially correlates to the findings of the actual experiment. To do so, the state of the noise barrier and the surrounding area, considering elements like the geometry, physical characteristics, and placement of the noise barriers, as well as the topography and any other pertinent structures that may be present were modelled as close as possible to the on-site study done by Haron *et al.,* (2019). Table 1 shows the parameters that had been used to simulate the on-site study.

Table 1
Parameters that had been used to simulate the on-site study done by Haron *et al.,* (2019)

Parameters	Value	Unit
Height of Barrier	4	Meter (m)
Thickness of Barrier	25	Centimeter (cm)
Noise Source Distance from the Barrier	17	Meter (m)
Noise Receiver Distance from the Barrier	6	Meter (m)
Noise Receiver Distance from the Ground	1.5	Meter (m)

Figure 2 depicts the lateral perspective of the on-site surroundings. The measured distance between the barrier and the noise source originating from the Skudai Highway is 17 metres. The spatial separation between the barrier and the Sound Level Metre (SLM) is 6 metres. The sound level metres were positioned at a height of 1.5 metres above the ground to simulate the typical stature of an average human being. The vertical dimension of the barrier measures 4 metres, while its horizontal dimension, or thickness, is 25 centimetres. The barrier measures 132 metres in length. The intermittent noise emanating from the secondary road was disregarded.

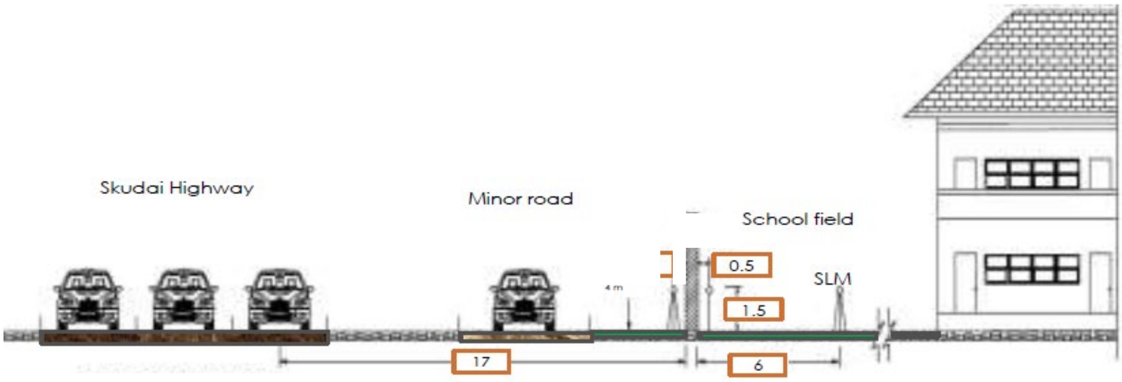


Fig. 2. Side view of the experiment environment [21]

Figure 3 and Figure 4 depict the schematic and the two-dimensional finite element model meshing of the system under investigation. The boundary conditions at the upper, right, and left edges are prescribed as Perfectly Matched Layers (PML). Given the specified boundary conditions, it can be observed that the waves propagating through the perfectly matched layer (PML) will exit the model system without experiencing any reflection [14]. The material properties of the concrete barrier, asphalt roadway, grass-covered soil and air used in the simulation are presented in Table 2. The study examined two barrier models: a flawless barrier wall and a barrier wall with a horizontal aperture measuring 2.5 cm, 5 cm and 10 cm in width located at the center. The barriers modelled in the study are impervious, meaning that no sound can pass through the barrier wall. This impervious condition does not really represent the condition of the on-site barriers. The aperture are added to the noise barrier to represent the cracks and perforations that are present within the on-site barrier. The aperture consists of straight, right angle edge opening that allow sound waves to pass through the centre of the barrier. The estimation of the range of a width of 2.5 cm, 5 cm and 10 cm was made based on an assumption. The noise emanating from the highway is represented in the model as a point source located in the lower left corner. A value of 55 dBA was assigned to the source to represent the maximum allowable noise level for outdoor school area recommended by the World Health Organization (WHO) [23].

Table 2
Material properties of the studied model used in the simulation

Materials	Density (kg/m^3)	Speed of Sound (m/s)	Acoustic Impedance (Pa.s/m)
Concrete Barrier	2300	3600	1.0×10^7
Asphalt Roadway	2200	2250	5.0×10^7
Grass-covered Soil	1600	200	3.4×10^5
Air	1.2	343	414

To replicate the conditions, present at the experimental site and generate visual depictions of the experiment's attributes, three model systems were generated. These systems included one without any noise barriers, one with a flawless barrier lacking any openings, and a third system featuring a barrier with set of apertures i.e. 2.5 cm, 5 cm and 10 cm width. Each model utilized approximately 200,000 elements. The determination of both the size and number of elements was calculated using the formula as provided by Papadakis and Stavroulakis (2018). The waves exhibit a distinct property known as wavelength (λ) in spatial dimensions, which is contingent upon the frequency (f) and the speed of sound (c) within the medium. This relationship is mathematically expressed as $\lambda = c/f$. To accurately represent a wave, it is necessary for the mesh components to be smaller than the wavelength, thereby ensuring proper resolution of the wave. To get the desired outcome, it is important to ensure the presence of several degrees of freedom per wavelength. The minimum size of the element's side length is defined by the shortest wavelength, corresponding to the maximum frequency being studied in this study, which is 2500 Hz. The simulations aim to accurately replicate the Sound Pressure Level (SPL) and assess the Insertion Loss (IL), a metric used to quantify the noise reduction provided by the noise barrier. The collected data are compared with the SPL and IL data recorded on-site to evaluate the credibility of the simulation. The verification of the simulation's precision and its ability to predict the acoustic effectiveness of noise barriers will be established by a strong correspondence between the simulated and measured data.

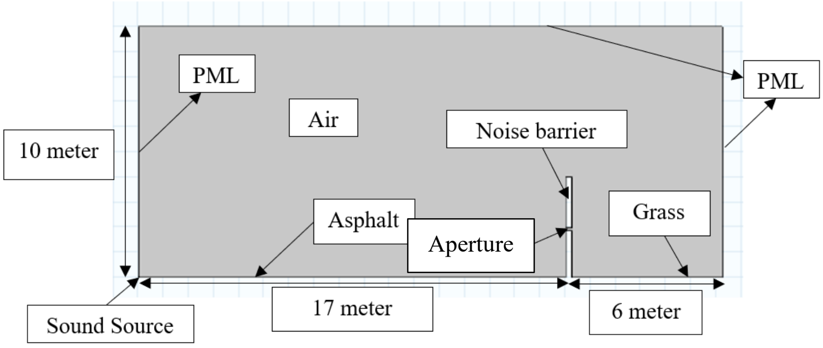


Fig. 3. Schematic of the 2-dimensional studied model

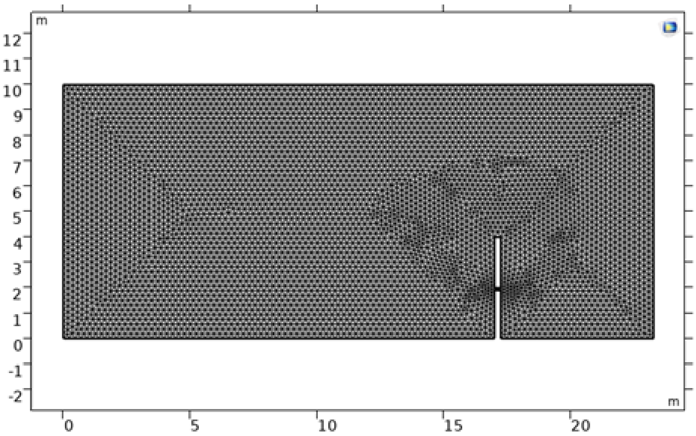
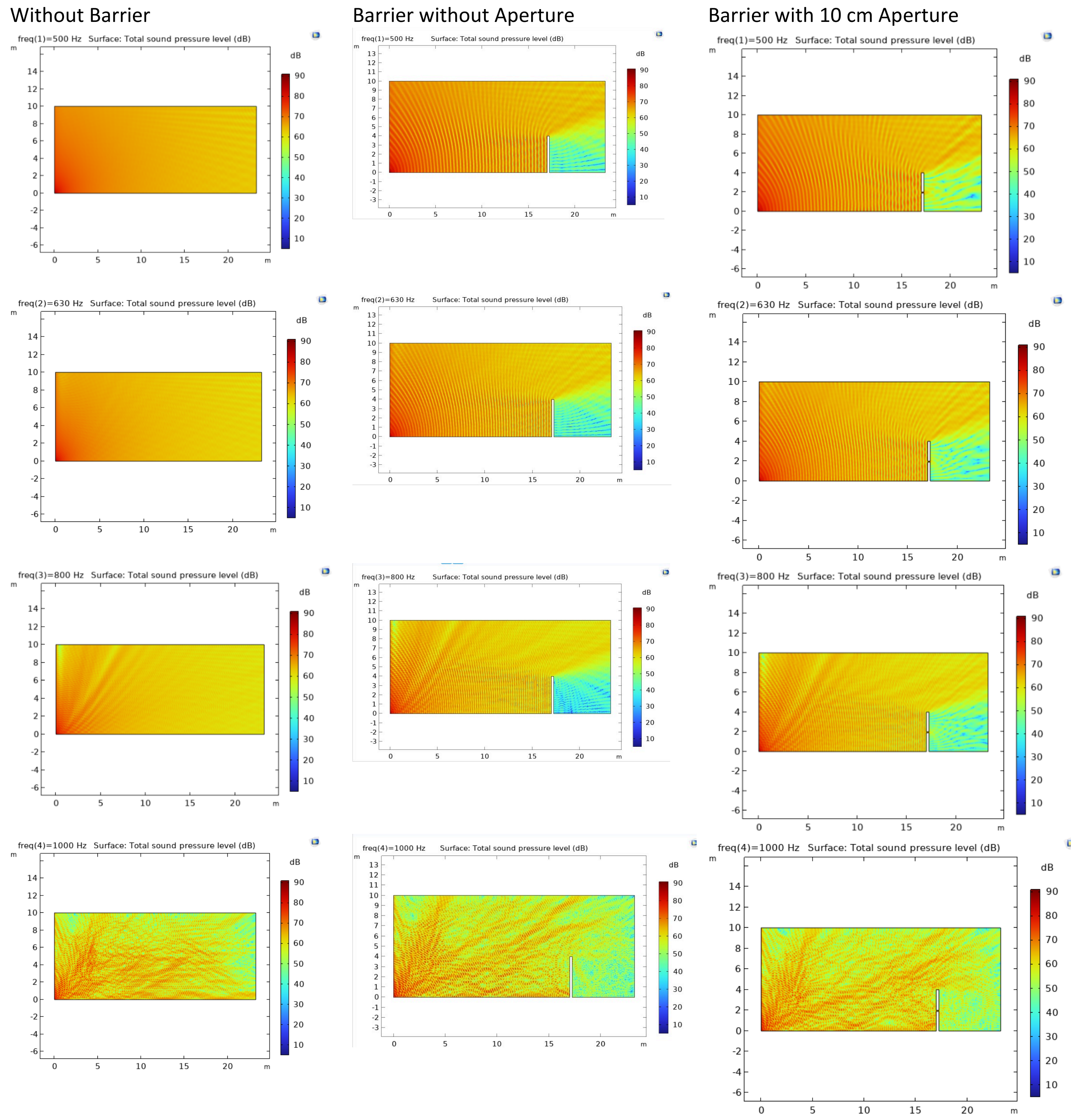


Fig. 4. Finite element model meshing

3. Results and Discussion

3.1 Evaluation of the SPL Simulation in 2-Dimensional Model

Figure 5 presents the two-dimensional simulations of the investigated systems at frequencies of 500Hz, 630Hz, 800Hz, 1000Hz, 1250Hz, 1600Hz, 2000Hz, and 2500Hz. The simulations included a comparison of sound pressure level (SPL) distributions among three different systems: one without a barrier, one with a barrier but no aperture, and one with a barrier featuring a 10 cm aperture. The presence of barriers has led to a noticeable decrease in sound pressure levels (SPL) on the right side of the barrier, specifically within the area of the school. A portion of the sound waves can permeate the barrier, while others are deflected above the barrier, and a further subset is reflected towards the left by the barrier. This phenomenon is consistent with the observations reported by Grahn and Jensen (2019). The imperfect barrier exhibited a higher degree of sound wave leakage compared to the ideal barrier. The presence of an aperture is indicated by a greater sound pressure level (SPL) on the right side of the barrier. Another notable fact is that waves with lower frequencies have a greater ability to traverse longer distances compared to those with higher frequencies. The phenomenon described can be discerned by examining the distribution of sound pressure level (SPL) across a range of frequencies, starting from lower frequencies, and progressing towards higher frequencies. Figures with lower frequencies exhibit a contour that is characterized by an orange colour, while figures with higher frequencies display a contour that is characterized by a greenish tint. This occurrence is consistent with the observations reported by Grahn and Jensen (2019). The simulations presented in this study demonstrate the superiority of finite element analysis in comparison to experimental or theoretical analysis methods in terms of visualizing the distribution of sound pressure level (SPL). The efficacy of noise barriers can be assessed using visual analysis.



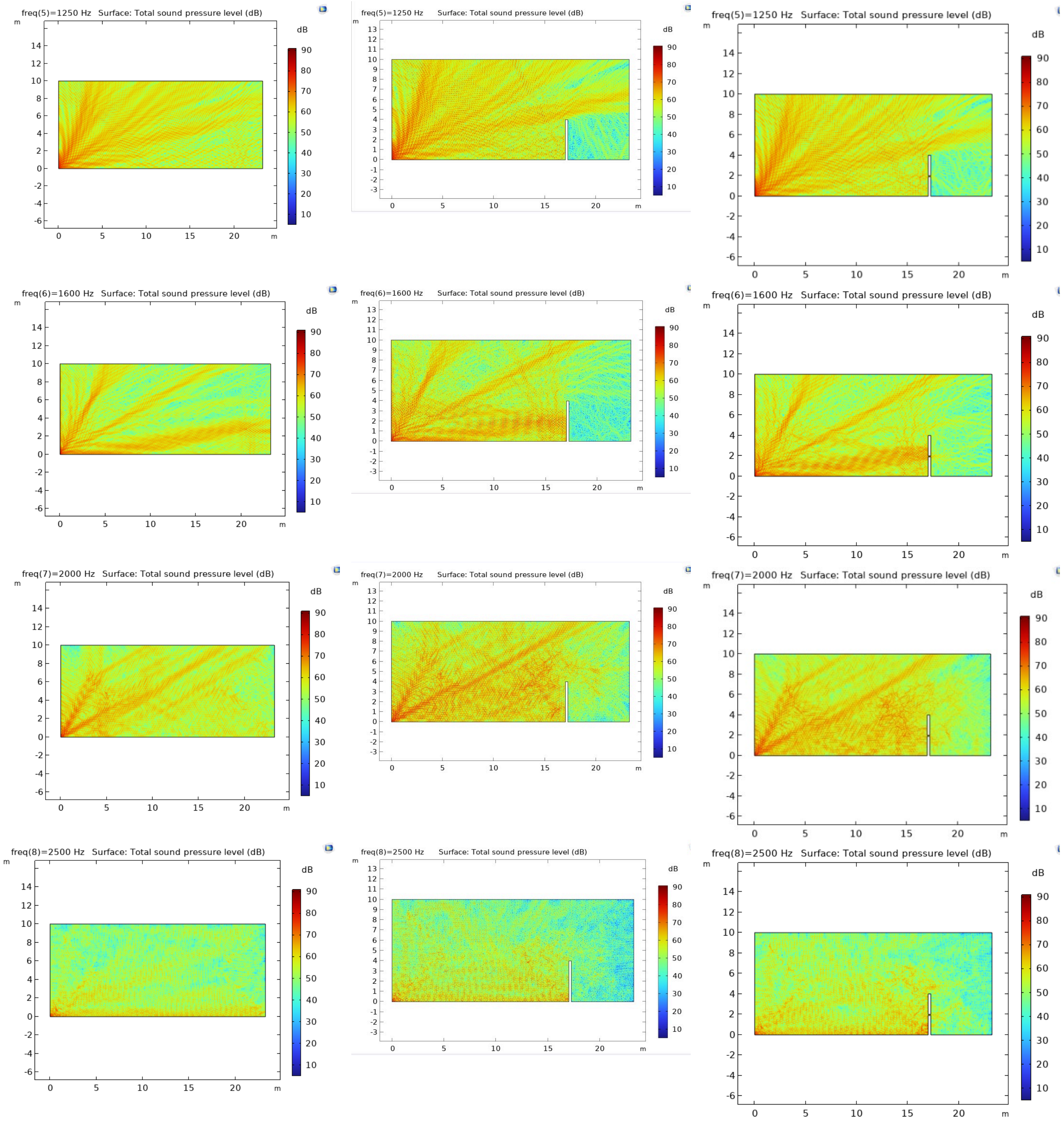


Fig. 5. Comparison of simulations of the investigated systems at frequencies of 500Hz, 630Hz, 800Hz, 1000Hz, 1250Hz, 1600Hz, 2000Hz, and 2500Hz

3.2 Evaluation of the Sound Pressure Level

Figure 6 presents a comparative analysis of the Sound Pressure Level (SPL) derived from simulated data and on-site measurements conducted by Haron *et al.,* (2019). The SPL plots depict the impact of the presence or absence of a sound barrier, offering insights into the barrier's efficacy in noise reduction. To provide a comprehensive view, A-weighted SPL data were collected in 1/3 octave band frequencies ranging from 500 to 2500 Hz. Measurements were taken at a specific location—6 meters behind the barrier and 1.5 meters above the ground. The use of A-weighting aimed to better represent the auditory experience, aligning with the sensitivity of the human ear across different frequencies. Upon examination of Figure 6, a notable trend emerges: the on-site measured data consistently exhibit higher SPL values compared to the simulated data. This discrepancy can be attributed to various external factors, such as ambient noise from the adjacent minor road (as depicted in Figure 2), noise emanating from the school premises, and other human activities in the vicinity. Remarkably, both sets of data display a distinctive peak at 1000 Hz, aligning with findings from a prior study by Rochat and Reiter (2016). The study highlighted that the spectral content of noise generated by passenger vehicles often peaks around 1000 Hz [24]. This correlation underlines the reliability of the observed frequency distribution in the current investigation. Simulated sound data has more intricate patterns than on-site measurements. Moreover, the impact of the sound barrier becomes evident in the data, revealing a noteworthy reduction in sound energy of approximately 5 dBA for both simulation and measured data. This outcome underscores the barrier's effectiveness in mitigating noise, substantiating its role as a valuable intervention in reducing the overall sound exposure at the specified measurement point.

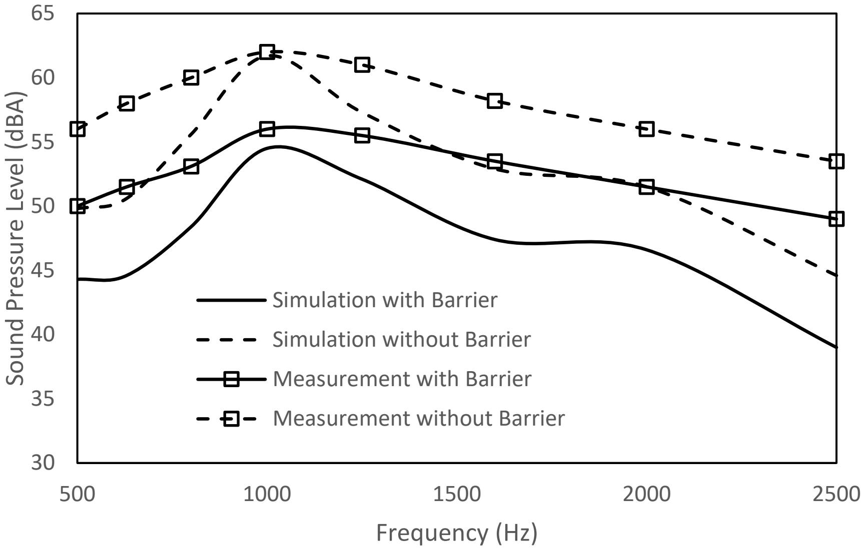


Fig. 6. Comparison between Sound Pressure Level of simulated and on-site measured data

3.3 Evaluation of the Insertion Loss

Figure 7 illustrates a comparison of the Insertion Loss (IL) for a simulated barrier without an aperture, a barrier with a 2.5 cm, 5 cm and 10 cm aperture, and on-site measured data. Insertion Loss serves as a metric to gauge the effectiveness of a noise barrier in minimizing sound transmission from one side to the other. As expected, the simulation of the barrier without an aperture exhibits a higher IL compared to the barrier with a 10 cm aperture, reflecting the anticipated impact of noise leakage through the aperture. The on-site measured data aligns well in between the simulated data, reinforcing the notion that some degree of noise leakage may be occurring through the wall barrier. This leakage could be attributed to cracks and perforations present in the on-site barrier. Decreasing the aperture width results in a closer alignment between the IL and the on-site measured data. This pattern is evident in the simulation with apertures measuring 5 cm and 2.5 cm. However, there are noticeable IL gaps at ~1000 Hz and ~2000 Hz range between the measured data and the simulation with 10 cm aperture. These relatively larger gaps may be attributed to the influence of diffraction via the apertures. The gaps were reduced as the aperture sizes decreased.

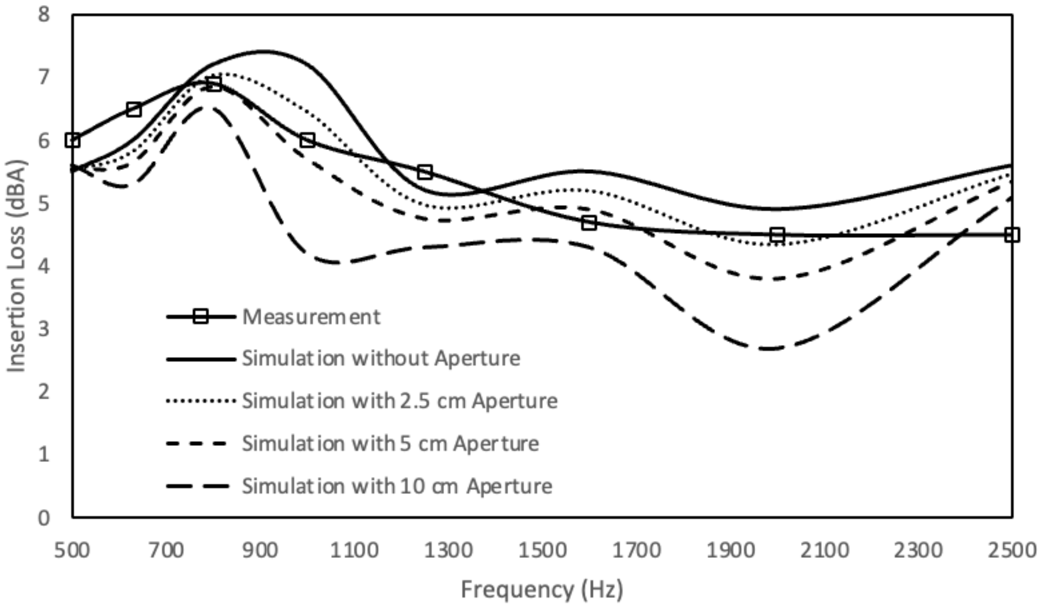


Fig. 7. Comparison between Insertion Loss of simulated barrier without aperture, with 2.5 cm, 5 cm, 10 cm aperture and measured data

Table 3 presents a comparison of Insertion Loss Difference between the simulations and measurements conducted by Haron *et al.,* (2019). The difference is calculated by finding the absolute disparity between the simulated IL values in the absence and presence of 10 cm, 5 cm and 2.5 cm apertures against the on-site measured data. The simulations explored barriers with and without aperture, aiming to illustrate the impact of sound leakage on IL performance. The average difference values, in the absence and presence of the 10 cm, 5 cm and 2.5 cm apertures, stand at 0.6 dBA, 1.1 dBA, 0.5 dBA and 0.4 dBA respectively. These results align with expectations, given the presence of bigger sound leakage in barriers with apertures, resulting in a higher diminished IL performance. The disparities between the simulated IL without and with an aperture, relative to the measured data, are minimal—from 0.4 dBA to 1.1 dBA. These findings underscore a commendable concordance between the simulated and measured IL values. The suggestion emerges that there exists an opportunity for refinement in the simulated IL. This can potentially be achieved through the fine-tuning of aperture sizes aiming to bring the simulated IL values into closer alignment with the measured data. In essence, these findings not only unveil the dynamics of sound leakage on IL but also point towards a pathway for enhancing the precision of simulated IL through strategic adjustments.

Table 3
Comparison of Insertion Loss Difference, |Diff.| between simulation and measurement for barrier without and with 2.5 cm, 5 cm, 10 cm aperture

Frequency (Hz)	Without aperture (dBA)	With 10 cm aperture (dBA)	With 5 cm aperture (dBA)	With 2.5 cm aperture (dBA)
500	0.5	1.6	0.5	0.4
630	0.5	1.2	0.9	0.5
800	0.3	0.4	0.0	0.1
1000	1.2	1.8	0.3	0.4
1250	0.3	1.2	0.8	0.5
1600	0.8	0.4	0.2	0.5
2000	0.4	1.8	0.7	0.1
2500	1.1	0.6	0.9	0.9
Average	0.6	1.1	0.5	0.4

4. Conclusions

In conclusion, this study meticulously explores the multifaceted relationship between highway noise, noise barriers, and the effectiveness of Finite Element Modeling (FEM) in simulating acoustic solutions. The expansion of transportation infrastructure and the resulting surge in highway networks have underscored the urgent need for mitigating noise pollution, emphasizing the importance of noise barriers. The study introduces the COMSOL Multiphysics FEM program, designed for simulating acoustic problems, and critically examines its accuracy in representing the efficacy of highway noise barriers. By validating the FEM predictions against empirical data from an experimental study conducted by Haron *et al.,* (2019), the research ensures a robust foundation for guiding noise mitigation strategies. The simulations, meticulously aligned with the on-site conditions, demonstrate the superiority of FEM in visualizing sound pressure level (SPL) distributions and assessing Insertion Loss (IL). The study not only provides a thorough comparative analysis of simulated and measured data but also highlights the potential for refining FEM simulations through adjustments in aperture sizes. Overall, this research significantly contributes to the discourse on sustainable urban development and transportation planning by addressing the critical issue of noise pollution, offering insights for urban planners, architects, and researchers striving to create quieter and more livable urban environments.

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