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THE DESIGN OF A SONIC CRYSTAL NOISE BARRIER FOR AN EVOLVING URBAN AREA

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ABSTRACT

This study examines the urban transformation of the area around Terracini Street in Bologna, Italy, from a suburban industrial zone to a residential and university area over the past two decades. The research analyses the site's morphological and infrastructural characteristics, evaluates relevant acoustic and urban regulations, and measures environmental noise levels. Proximity to a heavily trafficked road has resulted in significant noise limit exceedances in public spaces. The study also includes a finite element method (FEM) analysis. This analysis evaluates the barriers' acoustic performance and integration into the urban environment. A novel noise barrier design is proposed, utilising the sonic crystal technique to mitigate the noise impact on the University premises. This approach achieves an average noise reduction of 10 dB(A) in the 200 Hz to 1 kHz range while maintaining visual transparency and air ventilation. The design considers the barrier's ecological and aesthetic impact, aligning it with the area's new identity as home to the University's School of Engineering. The findings offer insights into innovative noise mitigation strategies and highlight the potential for applying acoustic metamaterials in similar urban contexts.

Keywords: *Urban transformation, Noise barrier, Acoustic metamaterials, Sonic crystals, Environmental noise.*

1. INTRODUCTION

Over the past decades, urban expansion has raised concerns about environmental noise [1]. Various disciplines, including Urban and Environmental Engineering, Acoustics, and Sociology, have studied this issue through historical analysis, regulatory evaluations, and community engagement [2–6]. Participatory tools like focus groups and sound walks aid in assessing public opinion [7]. Noise-reducing measures include low-noise pavements, noise barriers, and soundproofing solutions for critical buildings [3,8]. Noise barriers effectively reduce traffic noise but can have visual and ecological impacts [9]. Innovative designs using metamaterials offer solutions that allow noise reduction while maintaining air passage and transparency [3,4]. This study assesses the environmental noise around Terracini Street due to increasing traffic and proposes a sonic crystal noise barrier for the University campus. The design strikes a balance between noise mitigation and urban functionality, preserving pedestrian access and emergency routes.

2. METHOD

2.1 Urban Development of the Navile District and Noise Regulation Regarding the Studied Area

The Navile district has transitioned from an industrial and agricultural area to a residential and university hub over the past 20 years. Urban expansion and increased traffic, particularly on Terracini Street near the University of Bologna's School of Engineering, have led to significant noise pollution, with 38,000 vehicles daily exceeding noise limits and impacting study and work environments [4,5].

Italian noise control laws have evolved since 1995, establishing legal limits for urban noise pollution. Framework Law No. 447/1995 assigns responsibilities to institutions for noise management [10]. Further regulations, such as D.P.C.M. 14 November 1997, define noise limits for different urban areas [11]. According to Bologna's acoustic zoning, the university site falls into Class III, with limits of 60 dB(A) during the day and 50 dB(A) at night [11,12].

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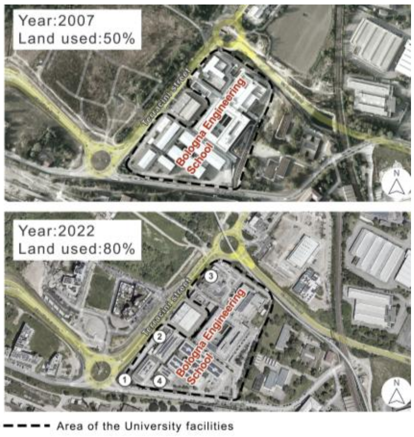

Figure 1. The historical development of the area around Terracini Street in the Navile District. The yellow lines depict the current road infrastructure, including Terracini Street. The black dashed lines mark the perimeter of the land associated with the University facilities where measurements were taken. The measurement points within the area near Terracini Street in Bologna studied are indicated.

2.2 Preliminary Assessment of Terracini Street's Environmental Acoustics and Numerical Design of a Novel Noise Barrier

Noise monitoring was conducted at various points along Terracini Street to assess traffic-related noise levels (Figure 1). To determine if the noise limits for acoustic class III in the studied area are exceeded according to Italian regulations (Upper Limit Values for $L_{Aeq,day}$ and $L_{Aeq,night}$ are respectively 60 and 50 dB(A)), L_{Aeq} measurements were conducted over 24-hour. The sound level meter was placed 4 meters above street level, at least 1 meter away from buildings, and in conditions with no precipitation and wind speeds under 5 m/s, as required by the regulations [13,14]. The measurement points were selected to cover the entire length of Terracini Street adjacent to the University buildings, spanning from one roundabout to the other (see Figure 2). Two sound level meters (DUO 01dB Metravib), compliant with IEC 61672-1 class 1, were used for the measurements. The acquired data was processed using the dBTrait software.

Then, a sonic crystal acoustic barrier (SCAB) was selected as the optimal solution for noise mitigation. Sonic crystals, structured periodic arrays, manipulate sound waves based on geometry rather than material properties, allowing air ventilation and solar control while reducing noise [3]. Using Maekawa's method, the required barrier height was determined based on insertion loss (IL) targets, accounting for source-receiver distances and frequency-dependent attenuation. IL Target was set at 8–13 dB(A) depending on the section of the street [4].

A Finite Element Method (FEM) model was created in COMSOL Multiphysics to simulate the acoustic performance of a noise barrier combined with low-noise asphalt (Figure 2). It included omnidirectional sound sources representing vehicle noise and boundary conditions mimicking real-world propagation. Sonic crystal barriers were modeled using absorption coefficients from previous studies [3]. Noise propagation along Terracini Street was simulated with four linear sources (one per lane) and a receiver (R in Figure 2), positioned according to ISO 1996-2-2017 at 4 m above the ground and 1 m from the nearest building façade. A hemispherical domain was used for free-field sound propagation, with four circular sources per lane (r = 0.5 m) generating omnidirectional sound waves at 1 Pa (94 dB), placed 0.5 m above ground to reflect vehicle noise.

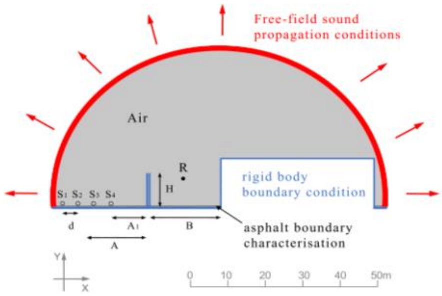

Figure 2. Sketch of the 2D numerical setup and boundary conditions for Section A (which is representative of all the sections analyzed), with H=5 m, A=13.1 m, A1=7 m, and B=22 m. The red line indicates the free-field sound propagation conditions, modelled by a hemispherical domain, while the blue line marks the rigid body boundary condition on the external surfaces of the building. The circles, labeled S1, S2, S3, and S4, represent the four sources corresponding to the four street lanes within the section, each spaced 3.5 meters apart. R denotes the receiving point.

The red line in Figure 2 represents simulated free-field sound propagation, while the blue line marks acoustically reflective building façades. Since noise pollution mainly affects areas within 10–30 m of the road, the model included a 50 m radial distance from the barrier's base.The FEM model assessed the barrier's effectiveness using Insertion Loss (IL), comparing noise levels before and after intervention. The design IL_{Design} was calculated in the 200–1000 Hz range as the A-weighted difference between pre- and post-intervention sound pressure levels at the same receiver. The overall values were reconstructed from one-third octave band data, using the formula:

$$IL_{Design} = SPL_{without} - SPL_{with} \text{ [dB(A)]} \quad (1)$$

3. RESULTS

3.1 Preliminary monitoring results

Noise exceedance was recorded at all monitored locations, with daytime levels exceeding limits by 9 dB(A) and nighttime levels by 13 dB(A). The survey revealed that noise levels remained consistently above the regulatory limits for several hours during both day and night. Measurements taken at the first three locations indicated higher sound levels compared to those recorded at the fourth location, situated on Lazzaretto Street. The observed difference, ranging from 5 to 13 dB(A), is likely due to the lower traffic volume on Lazzaretto Street. Its designation as a dead-end street results in significantly reduced vehicle circulation, leading to lower noise levels. Traffic reduction alone would be insufficient for effective noise mitigation, necessitating a combination of measures such as low-noise asphalt and noise barriers.

3.2 FEM Study Results

The upper part of Figure 3 presents a colour map illustrating the spatial distribution of the sound pressure level (SPL) at 1 kHz, derived from the FEM 2D analysis of sections A–D. The figures clearly indicate that before the proposed intervention, SPL was notably high across most points in the sections. However, following the implementation of noise mitigation measures, a significant reduction in SPL was observed. The applied solutions effectively lowered the sound pressure level, achieving an average insertion loss (IL) of 10 dB(A) within the relevant frequency range of 200–1000 Hz.

Figure 3 (top) displays the Insertion Loss (IL) derived from the A-weighted SPL spectrum across the 200 Hz to 1 kHz frequency range, measured in 5 Hz increments at receiver point R in section A (refer to Figure 2). Positive IL values indicate a reduction in noise disturbance at each frequency. The IL plot reveals an average IL of 10 dB(A), with maximum reductions reaching up to 25 dB(A) at certain frequencies above 600 Hz. Furthermore, the IL trend is analyzed in Figure 3 (bottom); it emphasizes a significant IL increase - above 10 dB(A) - beyond 500 Hz. At lower frequencies (between 200 and 500 Hz), the FEM analysis reports IL values starting from 5 dB and above.

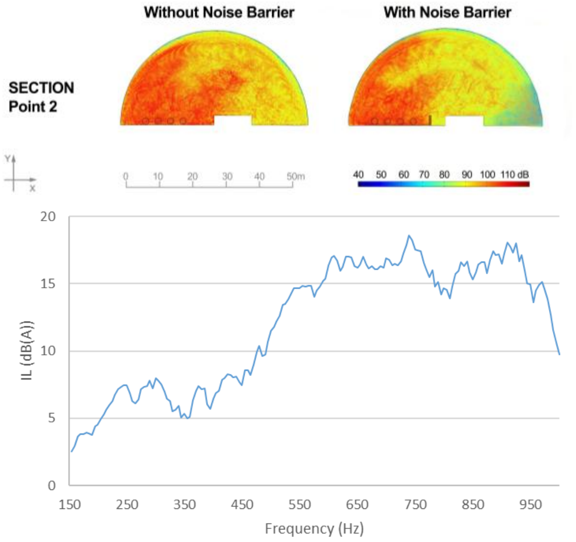

Figure 3. Upper: Spatial distribution of SPL based on the 2D FEM analysis on Point 2 at 1k Hz; left column: without the noise barrier; right column: with the noise barrier. Lower: A-weighted IL spectrum between 200 Hz and 1k Hz in section A as calculated in the 2D FEM analysis, considering the A-weighted SPL with and without the placement of the noise mitigation measures (noise barrier from ref. [3]) and low-noise asphalt from model 2-5 in ref. [15]).

4. CONCLUSIONS

This study examined noise pollution at the Engineering School of Bologna on Terracini Street, where traffic noise exceeds daytime legal limits by 9 dB(A). Measurements recorded 1216 vehicles per hour, with noise levels reaching 82 dB(A). Since traffic restrictions are not feasible, a combined mitigation approach was proposed: a low-noise road pavement and a sonic crystal-based noise barrier (SCAB). Using Maekawa's method, the SCAB was designed with variable heights (4–8 m) to optimize noise reduction while considering lighting, shading, and ventilation. The SCAB could lower noise by up to 25 dB(A) while maintaining urban aesthetics and airflow. This solution enhances environmental acoustic studies, demonstrating its potential for noise control in multifunctional urban areas without compromising urban quality.

5. ACKNOWLEDGMENTS

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