Journal of Applied Sciences

ISSN 1812-5654

OPEN ACCESS Journal of Applied Sciences
ISSN 1812-5654
DOI: 10.3923/jas.2023.178.184

Research Article

Explore the Common Measuring Errors and Quantify the Errors of New Noise Barrier Designs for Mitigating Traffic Noise

[1]Kai Long Mak, [2]Wai Keung Anthony Loh and [2]Chun Kit Wilson Kwan

[1]Kent Business School, University of Kent, Canterbury Campus, Canterbury CT2 7NB, United Kingdom
[2]School of Professional Education and Executive Development, The Hong Kong Polytechnic University (PolyU SPEED), Hung Hom Bay, Hong Kong

Abstract

Background and Objective: Noise pollution from road traffic has been a persistent problem in Hong Kong and there has been increasing attention on its association with risks to human health and well-being. Much research has been done in searching for an improved design of noise barriers as a direct noise abatement solution. Reflecting on the experience of supervising a recent acoustic barrier design project involving open field tests and using prototypes, this paper aims to explore the common errors in working and performing experiments with scaled models. **Materials and Methods:** The project team conducted tests in an open field for the three designs of noise barriers. Amplifiers were used to mimic traffic noise of 800-1200 kHz. The 3-D printing was deployed to make templates for casting concrete panels for their noise barrier models. **Results:** Test results showed some inconsistency with the team's expectations. All models were capable of reducing sound at all the measurement points of different heights. At lower heights, the reduction was 4 to 11 dB(A), At higher heights, the reduction decreased to only 3 to 5 dB(A). When the data were plotted on a graph, sound measurements of all three designs showed a non-linear path by height. Therefore, it was difficult for the team to draw convincing conclusions from them. There are lessons learned at every stage of the project, from idea formulation to prototyping and experimentation. **Conclusion:** Hopefully, these lessons and suggested resolves will help in the future, especially those involving the use and testing of scale model prototypes.

Key words: Noise barrier, prototypes, scaled model, measurement errors, model fabrication

Citation: Mak, K.L., W.K.A. Loh and C.K.W. Kwan, 2023. Explore the common measuring errors and quantify the errors of new noise barrier designs for mitigating traffic noise. J. Appl. Sci., 22: 178-184.

Corresponding Author: Kai Long Mak, Kent Business School, University of Kent, Canterbury Campus, Canterbury CT2 7NB, United Kingdom

Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Road traffic noise is a major concern in Hong Kong as a high proportion of our population dwells near heavily trafficked highways. Besides deterioration in the quality of life, it has serious health impacts, particularly on the cardiovascular[1] and immune systems[2]. Road traffic noise levels depend to a large extent on the volume, speed and mix of vehicle types. To protect the environment, Government has implemented policies to encourage the use of electric vehicles. However, research shows that the noise they produce is at comparative levels with vehicles with internal combustion engines (ICE). Both types of vehicles produce noise from tire friction with road surface pavement.

One of the most commonly used sound abatement measures in Hong Kong is erecting noise barriers along heavily trafficked highways to reduce noise levels in residential areas. Government Highways Department (HYD) and Environmental Protection Department (EPD) have issued strict guidelines on their design and construction and there are constraints including their wind load, availability of pavement space for their structural base, aesthetic appearance, costs, etc. In a 2006 Legislative Council Research Paper, experts opined that the aim should be placed on improving barrier edge design instead of on material use because Hong Kong had been using the best available material in the market already and more advanced materials cost much more higher. What followed was further research efforts in acoustic barrier designs that were conducted in laboratories.

Min and Guo[3] used analytical prediction models to assist in designing a sound absorber with a micro-perforated panel of different sub-cavity depths. They used COMSOL, a commercially available software, to assist in their numerical validation before proceeding to build and test prototypes. Kushwaha[4] performs numerical calculations on two-dimensional SC to search for improved attenuation performance (or "BG engineering") by experimenting with different lattice densities, i.e. by varying cylinder sizes (diameters) and filling fraction (a ratio reflecting the spacing of cylinders in the array). Herrero *et al.*[5] used a multi-scattering method to model the acoustic wave scattering process of a two-dimensional sonic crystal acoustic screen and calculated the attenuation ability of each sample.

Over time, much progress has been achieved on designs and materials used in noise barriers. Through years of supervising research studies in the testing of scale model prototypes, there are observable common pitfalls in experimenting with prototypes. These lessons happen repeatedly although in different fashions. While project ideas and objectives are worthy calls, the team's effort is highly commendable and their input is much appreciated, the outcome of projects may not always generate the desired results or serve the project purposes. A recent project on designing noise barriers with acoustic metamaterial is used to demonstrate observations of issues commonly happening in projects that involve testing of prototypes and scaled models. These pitfalls and misconceptions can undermine the usefulness of the prototyping process and render the results of the experiments non-conclusive or even misleading. This paper aims to offer some thoughts on how to combat these pitfalls and misconceptions and suggest means to improve the prototype and model-building and testing processes.

MATERIALS AND METHODS

Study area: A project by third-year students carried out from 1st September, 2022 to 31st July, 2023 was referenced in this paper. The work was conducted inside the noise laboratory at The Hong Kong Polytechnic University in Hong Kong. General measurement errors in the testing of prototypes were summarized.

Design selection: The idea of solving the traffic noise exposure problem is highly relevant as a large percentage of the Hong Kong population is exposed to it. In general, the research team dissected different elements of traffic noise and decided to test with a frequency of 1000 Hz. Three popular designs were related to acoustic wave behaviour on a curved surface. Ishizukan and Fujiwara[6] design was first selected for review for the effectiveness of top-edge design in reducing noise diffraction and thereby, increasing insertion loss of the barrier. Besides its aesthetic appeal, the concave dents provided space for road furniture. The second design was a barrier wall which consisted of a series of parabolic (concave) surfaces facing the traffic but with no additional top-edge design. Light-weight sound absorbing material was added at the focal point to dampen sound concentration. The advantages of this design were its relatively low cost to manufacture and ease of installation and adaptation to different road environments. The third design was a result of utilizing the first design with an addition of a rigid concrete wall behind the waveform barrier. Instead of a curled edge, a 45-degree cantilever top edge was added, which was supported by columns inserted inside the hollow between the wave wall and the rigid wall. To further enhance its noise attenuation performance, filling material was added to the hollow. Out of the three designs, the third one was the most difficult and expensive to fabricate.

Measurement setting: The prototype building and testing process required an understanding of acoustic wave theory. Project experiments involved fabricating prototypes of a reduced scale because it was not feasible to test a full-scale physical model. Real-life testing, i.e., installing physical prototypes on the roadside, also was not feasible because this would require permission from the Government as well as real-estate management and owners. Faced with limited funding and a lack of suitable sites for full-scale testing, the team resorted to conducting tests with models of a reduced scale of 1:12. The intended noise barrier height was 5 m. On a 1:12 scale, models of a height of 0.42 m were built. The tested insertion loss in the shadow zone behind the barriers at 5 heights, namely 1.7, 10, 15, 30 and 45 m, represented urban dwellers' exposure on different floors in buildings. On a 1:12 scale, the heights for setting receivers would be 0.141, 0.833, 1.25, 2.5 and 3.75 m, respectively. Tests were run with a sound frequency of 1000 Hz to resemble the frequency of tire noise. The 3-D printing was deployed to make templates for casting concrete panels for their noise barrier models.

An anechoic chamber was not used for testing because the chamber was not available at its desired time frame. Without an anechoic chamber, the model test was conducted in an open field, with a background noise level of the surrounding environment measured at over 60 dB(A). All measuring pieces of equipment were properly calibrated, mounted on poles of the prescribed heights mentioned above and were kept 0.54 m behind the barrier (6.5 m on a 1:12 scale) from the model barrier. The amplifier, which was the sound source, was placed 0.29 m in front of the model barrier (3.5 m on a 1:12 scale) and 0.08 m (1 m on a 1:12 scale) above ground level. The team considered that these distances were reasonable in avoiding bounce back of noises and at the same time, representative distances of traffic noise sources from vehicles and of Hong Kong's urban environment. The team chose to conduct the experiment during non-peak traffic hours in order to reduce the impact of background noise in the open field on their measurements.

The project team conducted tests in an open field for the three designs of noise barriers. Amplifiers were used to mimic traffic noise of 800-1200 kHz. All measuring pieces of equipment were properly calibrated and kept from a reasonable distance from the sound source to avoid bouncing back. The distance from the sound source to the noise barrier model was 0.29 m, which represented a horizontal distance of 3.5 m on a 1:12 scale and the distance from the sound source to the receivers was 0.83 m, which represented a distance of 10 m on a 1:12 scale. The experiment was conducted on a day with low humidity to ensure the proper functioning of equipment and the accuracy of measurements taken. The team chose to conduct the experiment during non-peak traffic hours in order to reduce the impact of background noise in the open field. The team made use of 3-D printing in the manufacturing process of the barrier models.

RESULTS

Noise measurements from the experiment for all three models were compared for their overall performance. All models were capable of reducing sound at all the measurement points of different heights. At lower heights, the reduction was 4 to 11 dB(A), at higher heights, the reduction decreased to only 3 to 5 dB(A). When the data were plotted on a graph, sound measurements of all three designs showed a non-linear path by height. The paths for all designs were not smooth and there were kinks at some points of height on some days, which demonstrated a pattern inconsistent with the team's initial expectations. The team attributed these inconsistencies to background noise. The team also observed that the difference in the sound attenuation ability reduced from 1.25 m onwards and there was little difference among the three designs at 3.75 m.

The team compared the performance of the three designs and concluded that the wave pattern of the barrier wall was a better performer in sound attenuation and the third design was chosen for further testing of the performance of different materials. Cement was used in producing the barrier walls and tests were performed with a hollow barrier, one stuffed with spray cotton and a full concrete barrier. Based on results observed in the last stage of the experiment, barriers were built up to 2.5 m in height for this stage of testing of material. Results showed that concrete barriers stuffed with spray cotton performed better than the other two. The concrete barrier stuffed with spray cotton was able to produce attenuation of 1 to 8 dB(A) at various heights and full concrete was 1 to 5 dB(A). The hallow design showed negative performance in some instances, due to resonance within the hollow. Data on some days showed a decrease in performance as height increased and there were instances of negative results above 1.25 and 2.5 m, such inconsistency at 2.5 m could be caused by noise diffraction at the top edge of the barrier. The team was not able to conclude concrete was a good sound-absorbing material based on these results. The team experienced difficulties at an early stage of their experiment in putting their various ideas into working models and in fabricating models due to budget constraints and a lack of experience in working with the materials.

DISCUSSION

Experimenting on a reduced-scale model is very useful to test design variations, test and compare theories, as well as predicting design performance results of a full-scale model. It is vital as a first step in deciding on using a reduced-scale model to consider the scaling laws that apply. This is essential for deciding the prototype scale because the relative strengths of the forcing factors must be reproduced correctly in order that tests performed on the reduced-scale model to serve the purpose. Scaling laws are very useful in understanding the basic physical principles involved in many complex phenomena. They provide insights into the structural and functional consequences resulting from changes in size or scale among otherwise similar structures. In complex models scaling laws become relevant for understanding the interplay among various physical phenomena and geometric characteristics. Sometimes, relatively simple scaling laws, applicable to very complex models, can provide clues to some fundamental aspects of the system. If scaling considerations are neglected, model results can become either meaningless or misleading.

It was intended in this project that when working with the scaled models, the dynamic characteristics (e.g. frequencies, shapes and mass) should replicate their full-scale counterparts. However, appropriate scaling needs to be applied so that the experimental data of the scaled models to provide good predictions of the dynamic response of their full-scale counterparts. Since the noise barrier model was reduced to 1/12 but there was no corresponding adjustment to the frequency wavelength in the test, the prototype barrier was exposed to sound waves of wavelength 12 times larger than what the proportion the experiment had originally intended. Therefore, the test results would not be a reliable representation of the performance of their full-scale noise barrier designs.

Zhang *et al.*[7] conducted an experiment on using an ionic crystal structure as an outdoor noise barrier by building test prototypes of a 1:10 scale. Scatterers were built using cylindrical wooden bars 30 cm in height and 1.5 cm in diameter, the length of the barrier system was 100 cm. This represented at full scale 3 m in height, 15 cm in diameter and 10 m in length. The frequency range tested was of the 1/6-octave bands from 500 to 10 kHz (50 to 1000 Hz at full scale).

When working with scaled models, emphasis is placed on ensuring the characteristics or properties under the experiment are expressed and represented fairly through the combination of various parameters so that the change in size, i.e., scale, does not affect the performance of a model as predicted from the results. Scaling laws help to overcome erroneous application of personal intuition and perceptions. in the prototyping process and model design.

An anechoic chamber is a room designed to minimize reflections of either sound or electromagnetic waves. The thick wall and noise absolution material, isolate external noise and the chamber can be used to minimize sound reflection and also external noise. Anechoic chambers are widely used in noise experiments as it is the best way to simulate free-field (no reflected signals) condition in a laboratory.

An anechoic chamber is essential in simulating the acoustical conditions of the phenomena under test in an unobstructed free space. In this case, it would be sound wave propagation around and the insertion and transmission loss of the model noise barriers being tested. Without an anechoic chamber, the team resolved to conduct tests of their models in an open field that has a background noise level of over 60 dB(A). The project team noted there were multiple reflections of noise and incidents of disturbance during their tests and sound was able to diffract over the top edge and side edges of the barrier. It was no surprise that the insertion loss measured in the shadow zone of their models was low and the results non-conclusive. The project also noted how environmental factors such as temperature and humidity affect the propagation of sound, especially high-frequency sounds since the tests were done outdoors.

The importance of an appropriate testing site cannot be stressed enough and it is essential that options are explored thoroughly. Even anechoic chambers do not guarantee accurate results if their dimensions are not appropriate for the low-frequency range to be tested. In site selection, careful assessments must be made as to the factors and their extent of interfering with the essential parameters of the experiment that would have on the accuracy and reliability of test results and whether there are any means to adjust and mitigate their effect. Accurate free-field measurements can be obtained in a regular room without an anechoic chamber by making what is known as a “splice measurement”. This consists of a near-field measurement covering the lower frequencies and a time-windowed far-field measurement joined together in the range where both measurements are still valid and overlap. The near-field measurement is adjusted for the distance between the sound source to the receiver to simulate the free-field response of the appropriate distance. A time window is applied to the measurement to exclude reflections in measurement if leading and trailing cosine tapers are available.

A prototype experiment involves an incomplete representation of both the design structure and the environment the structure is supposed to be exposed. Therefore, the environment in which the testing of prototypes is conducted is crucial in ensuring reliable results. Kumari *et al.*[8] believe that the testing environment should be part of the iterative process that goes parallel with the iteration process of building a prototype. Vestad and Steinert[9] suggested that certain changes can be made to the testing environment when using an existing test environment in order that the environment fits the needs of the experiment. The performance measures of a test environment that are worth highlighting include the level of approximation in representing the real challenges for its application, whether results are explicit or implicit that require additional judgment and interpretation and how flexible the experiment is in accommodating changes in prototype design and test scenarios. In the noise barrier experiment under discussion, the project team resolved to use amplifiers in an open field when an anechoic chamber was not available. The team also noted multiple sound reflections in the open field and occasions of interference during their tests. The choice of a physical test site includes consideration of the site's environmental load and characteristics that are representative of the operating environment of the noise barrier structure. Given the high level of background noise (measured at over 60 dB(A)) and the uncontrollable interference, the team could have considered alternatives or control measures to ensure the reliability of the experiment results and fairness in comparison (e.g. choose a testing time that would be less prone to background noise influence, make improvements on the test site or even choose another site).

Prototyping is an indispensable part of the design thinking process. Prototypes can be used to convey ideas and obtain feedback to improve design ideas. Before prototyping, one needs to be very clear on what specific questions the project attempts to answer, good understanding of the parameters and phenomena or forces at work and test and validate assumptions.

In this project and as in any design process, there have been many design ideas and numerous iterations of feedback before the team finalized three designs but related to one common theme: Acoustic wave behaviour on a curved surface. Both the first and second designs had curved barrier walls but with different shapes of curved surfaces facing the traffic, therefore, they exhibited different acoustic phenomena. The third design was a modification of the first design with more enhancement features.

Because prototyping, especially the higher-fidelity version, can be expensive and time-consuming to fabricate, it is advisable that low-cost, low-fidelity versions (with readily available material like paper or cardboard) with just the level of detail required for brainstorming, can be used in the ideation process to help the team visualize proposed designs, analyze the parameters and forces involved in the experiment or in a real-life situation and assist the team to objectively evaluate the effectiveness of the design ideas in solving the problem the project aims to address. Such a cheaper or simplified alternative also acts to invite ideas and encourage the team to open their options. Once the low-cost prototype has served its purpose, it can be "destroyed" or put aside mentally so that the team can move on to other ideas or models as rapidly as possible to avoid becoming anchored to one stream of thought.

Numerical simulation is a means of helping to solve complex design issues, especially those that involve calculations and cannot be demonstrated easily in real life. Commercial software is available to assist. Numerical simulation has been used extensively in research, especially in solving complex calculations and design issues. In the optimization process, a parallel multi-objective evolutionary algorithm was employed to solve multiple objective questions. After fine-tuning and optimization, the resultant design showed an improvement in attenuation capability from their initial sample by almost three times!

The 3-D printing technology offers many advantages. Besides saving time and money in the design and fabrication process, the process can be completed with much higher precision. While none of us are craftsmen, enough attention should be given to the model fabrication process to cost estimation as well as the knowledge and experience needed to decide on a preferred fabrication method. The project team noted that the mixture of mortar was not consistent and there were errors in the measurements of the moulds, problems with the moulds, holding the weight of the concrete mixture, assembly problems, etc. In short, manufacturing and installation defects in the resultant panels might affect the fair comparison of the results of the three barrier designs.

Perhaps insights can be borrowed from a recent study by Choi and Zhang[10] which conducted surveys with industrial design university students before and after they fabricated models of products prescribed by choosing from the four methods: digital fabrication, computer numerical control, rapid prototyping using 3-D printing and handmade model making. Survey results showed a disparity in perceptions of methods pre-and post-fabrication. The complexity of the product design and the time needed to produce a model were the most important factors to participants in deciding which fabrication methods. Rapid prototyping was initially preferred, however, handmade model-making turned out to be the best-rated, most successful by the participants and appeared to be the most time-efficient.

There is no doubt that 3D printing is an amazing technology. However, its speed and convenience may lead to a false sense of security in the success of the designs. It is important that realistic measurements and levels of detail must be taken into account when using 3D printing especially if a conventional manufacturing or fabrication process is to follow after that. It is always beneficial to gain exposure to and a practical understanding of the advantages, disadvantages and time involved with a wide variety of fabrication methods before embarking on fabricating prototypes. This will help the project team to tailor their own approach to prototyping as their personal skills and experience.

While 3D printing, in bringing ideas and intentions into fruition, is expected to speed up the process for the designer to interact and obtain feedback with the model, both Gordon and Bieman[11] and Liou[12] noted that the resultant model may raise awareness of designers or users to certain features not apparent previously, thereby raises the prototyping cost and lengthens the time of the process. The designers have to decide which features are critical or primary that must be incorporated into the model for testing and which features are suppressed or secondary and, at the same time, ensures the performance of the resultant model, i.e. the predictability of its full-scale prototype, is not compromised. Liou[12] further highlights the importance of planning which includes resources and time and the allocation of resources when there are a number of models to produce and the choice of producing an analytical prototype over a physical one.

When there is more than one idea but very tight resources on building prototypes for each idea or iteration, a low-fidelity mock-up or simulation software may be able to help in validating ideas before building a scaled model for testing. By connecting parts and presenting ideas in a visual form, demonstrating relationships and shortfalls, low-fidelity prototypes facilitate students self-regulated learning by incorporating ideas and offloading feedback to refine their design in the scaffolding model.

CONCLUSION

The project team conducted an experiment on noise barrier designs of scaled models under a tight budget and high background noise levels. Being aware of the quality of the data collected and the reasons behind the inconsistencies, the team was not able to draw convincing conclusions from their experiment. This experience highlights the importance that enough care must be taken at every stage of the project, from idea formulation, design optimization, prototype and model fabrication, testing site selection and test environment fine-tuning, so that the project can be carried out to fruition. Through years of supervising undergraduate projects, some suggestions to avoid pitfalls commonly committed in projects, namely scaling, prototyping and managing the test environment, were offered here.

SIGNIFICANCE STATEMENT

Noise pollution from road traffic has been a persistent problem in Hong Kong due to cramped living conditions, poor planning of the past and buzzing economic activity. Noise barriers are the most commonly employed direct engineering solution in Hong Kong to combat the problem. In the search for a more effective noise barrier design, research is usually conducted in the laboratory by using prototypes or scaled-down models. There have been problems observed in designing, manufacturing and using these models. This study highlights the common problems observed in a recent student research project in order to bring to the attention of future projects, especially those involving the use and testing of scale models and prototypes.

ACKNOWLEDGMENT

The work described in this paper was fully supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. UGC/FDS24/E12/21).

REFERENCES

1. Münzel, T., M. Sørensen and A. Daiber, 2021. Transportation noise pollution and cardiovascular disease. Nat. Rev. Cardiol., 18: 619-636.
2. Zhang, A., T. Zou, D. Guo, Q. Wang and Y. Shen *et al*., 2020. The immune system can hear noise. Front. Immunol., Vol. 11. 10.3389/fimmu.2020.619189.
3. Min, H. and W. Guo, 2019. Sound absorbers with a micro-perforated panel backed by an array of parallel-arranged sub-cavities at different depths. Appl. Acoust., 149: 123-128.
4. Kushwaha, M.S., 1997. Stop-bands for periodic metallic rods: Sculptures that can filter the noise. Appl. Phys. Lett., 70: 3218-3220.

5. Herrero, J.M., S. García-Nieto, X. Blasco, V. Romero-García, J.V. Sánchez-Pérez and L.M. Garcia-Raffi, 2009. Optimization of sonic crystal attenuation properties by *ev-MOGA* multiobjective evolutionary algorithm. Struct. Multidiscip. Optim., 39: 203-215.
6. Ishizuka, T. and K. Fujiwara, 2004. Performance of noise barriers with various edge shapes and acoustical conditions. Appl. Acoust., 65: 125-141.
7. Zhang, Z., J. Wang, Z. Li and X. Zhang, 2022. Broadband sound insulation and dual equivalent negative properties of acoustic metamaterial with distributed piezoelectric resonators. Materials, Vol. 15. 10.3390/ma15144907.
8. Kumari, C.L., V.K. Kamboj, S.K. Bath, S.L. Tripathi, M. Khatri and S. Sehgal, 2023. A boosted chimp optimizer for numerical and engineering design optimization challenges. Eng. Comput., 39: 2463-2514.
9. Vestad, H. and M. Steinert, 2019. Creating your own tools: Prototyping environments for prototype testing. Procedia CIRP, 84: 707-712.
10. Choi, Y.M. and L. Zhang, 2015. Student perspectives on fabrication methods and design outcomes. Arch. Des. Res., 28: 49-61.
11. Gordon, V.S. and J.M. Bieman, 1995. Rapid prototyping: Lessons learned. IEEE Software, 12: 85-95.
12. Liou, F.W., 2007. Rapid Prototyping and Engineering Applications: A Toolbox for Prototype Development. CRC Press, Boca Raton, Florida, ISBN: 9781420014105, Pages: 562.