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The efficiency of the noise barrier installed on the acoustically untreated gallery

Эффективность шумозащитного экрана, установленного на акустически необработанной галерее

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Abstract. The research is targeting at multi-level overpasses which offer one of the solutions for laying the highway in conditions of dense residential development and close proximity to bedroom communities. In terms of acoustics, multi-level overpasses are semi-enclosed structures made of metal and reinforced concrete, where a complex sound field with numerous re-reflections is formed. There is no method of calculating noise from such structures in the literature of our country, therefore forecasting sound levels in the adjacent residential areas while designing noise mitigation measures is extremely challenging. The article proposes the method of calculating the efficiency of the noise barriers installed on the overpass edge based on the statistical theory of acoustics. The main assumption of the proposed model is the allocation of semi-closed volume in an acoustically untreated overpass and generation of a diffuse sound field in it, which is fundamentally different from the currently used methods for calculating the efficiency of the barriers installed in galleries as the barriers located in the open space, similar to motorways on the earth roadbed. When considering the diffuse field, the sound is not diffracted over the upper free edge of the barrier, but radiated outwards through the opening. According to the calculation results using the derived formulas, the efficiency of the barrier installed on the overpass does not exceed 2–6 dBA at its different heights, which corresponds to experimental results.

Аннотация. Объектами исследования являются многоуровневые автомобильные эстакады, которые являются одним из решений проложения автострады в условиях плотной жилой застройки и вблизи спальных районов. С акустической точки зрения многоуровневые эстакады представляют собой полузакрытые конструкции из металла и железобетона, где образуется сложное звуковое поле с многочисленными переотражениями. Методики расчета шума от подобных конструкций в отечественной литературе отсутствуют, в связи с чем прогнозирование уровней звука на прилегающих селитебных территориях при проектировании шумозащитных мероприятий является крайне затруднительным. В статье предложена методика расчета эффективности шумозащитных экранов, установленных на краю эстакады, основанная на статистической теории акустики. Основным допущением предложенной модели является выделение полузамкнутого объема в акустически необработанной галерее и создание в нем диффузного звукового поля, что принципиально отличается от применяемых в настоящее время методов расчета эффективности экранов, установленных на галереях, как экранов, располагающихся в открытом пространстве, аналогично автомобильным дорогам на земляном полотне. При рассмотрении диффузного поля звук дифрагирует не через верхнее свободное ребро экрана, а излучается наружу через проём. Результаты расчетов по выведенным формулам дают эффективность шумозащитного экрана, установленного на эстакаде, не более 2–6 дБА при разной его высоте, что соответствует результатам экспериментов.

1. Introduction

The problem of enhanced sound levels in the urban areas and communities is one of the most important worldwide. In order to reach the goal of providing the fastest possible transport connections, the new roads are built and the existing ones are expanded. Given the dense residential development, building of overpasses and multi-level galleries is often the only possible way. However, providing of the acoustically-safe conditions in the adjacent residential areas is also an important task.

In view of formation of a semi-enclosed space in the galleries, it is necessary to take into account the special conditions of noise propagation and reflection in an artificially created volume while designing noise mitigation measures. Otherwise, the developed noise protection measures, including installed noise barriers may not be effective or even worsen the acoustic environment. Thus, the research is targeting at multi-level overpasses.

Constructing galleries on the highway is a new phenomenon in the practice of road construction and the experience of the appropriate noise barrier application is virtually absent.

An overpass is referred to as a superstructure, which is an extended hollow metal engineering structure with enclosing structures of the cover and overlapping of various types. The general view of the structure is shown in Figure 1.

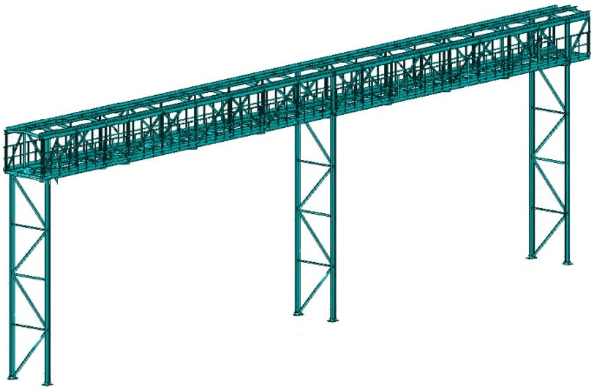

Figure 1. General view of the vehicle overpass

In general, three basic theories of acoustics can be applied to calculate the efficiency of the noise barrier: optical-geometric (geometric), wave and statistical [1, 2].

Optical-geometric theory considers sound as rays and takes into account diffraction phenomena. In 1818, A. Fresnel showed that diffraction can be explained by the application of the K. Huygens principle, which lies in the fact that each point of the disturbed medium is a source of the secondary waves. Later, D. Maekawa [2, 3–5] applied the ideas of the Fresnel-Kirchhoff diffraction theory for sources and noise barriers of different shapes, suggesting a well-known formula (1) as a calculation to determine the effectiveness of the noise barrier.

$$\Delta L_b = 10 lg 20N \quad (1)$$

$$N = \delta \frac{2}{\lambda}, \delta = A + B - d \quad (2)$$

)

where N is the Fresnel number calculated using formula (2);

δ is the path difference of the wave lengths, m;

λ – wavelength, m;

A is the distance from the noise source to the (upper) edge of the noise barrier, m;

B – distance from the reference point (receiver) to the (top) edge of the noise barrier, m;

d is the distance between the noise source and the target point (receiver), m.

U. Kurze [2, 6–8] suggested the formula (3) for calculation of the noise barrier efficiency, used in cases with a point source of noise.

$$\Delta L_b = 20 lg 20 \frac{\sqrt{2\pi N}}{th\sqrt{2\pi N}} + 5 \quad (3)$$

One of the main drawbacks of the optical-geometric theory is the impossibility of taking into account sound absorption and the length of the noise barrier.

The wave theory considers wave processes and is applicable to the calculation of the noise barrier efficiency using the boundary element method and the finite element method, which was first applied to the problems of acoustics by Gladwell and Zimmerman, who developed a General energy approach of the structural and acoustic theory to the solution of the differential Helmholtz equation, when the wave equation is converted into the form of a harmonic time dependence [9].

The disadvantage of the wave theory is the assumption that the noise barrier must be either perfectly reflective or perfectly absorbing, which is hard to achieve under real-life conditions.

Statistical theory is the most applicable for the calculation of the noise barrier efficiency because it allows to take into account the greatest number of influencing factors, namely the material and design of the noise barrier, changes in the nature of the sound fields when noise reduction structures are available.

Among the Russian authors, such scientists and researchers as N.I. Ivanov [1, 10], N.B. Tyurina [1, 2, 11], N.N. Minina [11], G.L. Osipov [12], P.I. Pospelov [13] and others researches [14–16] have been dealing with the problem of noise barriers and determining their efficiency. However, studying the efficiency of the noise barriers installed on the overpasses was considered only in the papers by N.I. Ivanov [1, 10], N.N. Minina [11] and N.B. Tyurina [1, 2, 11], and was based on determining the effective height of the noise reduction structures. Among the foreign authors, Malcolm Crocker made a significant contribution to the development of acoustics [17]. Investigation of noise barriers abroad is still carried out [18–20].

The author have not found any papers studying the noise barriers efficiency in the galleries.

Thus, the purpose of this study is the development and specification of the calculation methods for assessing the efficiency of the noise barriers installed in acoustically untreated galleries. The main objectives of the study are to substantiate the reliability of applying the statistical theory in assessing the efficiency of the noise barriers installed on acoustically untreated galleries and development of the calculation formulas.

The article deals with the calculation of the efficiency of the noise barriers installed on the vehicle overpass. The formulas for calculation of an overpass span, which is a semi-enclosed volume, are given. Open overpass spans, as well as overpasses located above the water surface, are not the subject of this paper.

2. Methods

The statistical theory of acoustics is suggested as the basis for engineering calculations. In order to apply it properly, it is necessary to take into account all acoustic processes occurring in the gallery, namely radiation, propagation, reflection, absorption and sound diffraction.

Due to multiple reflections of the sound from the metal arch of the gallery and road surface, a complex sound field close to diffuse is created in the gallery [2]. Overlapping of the apertures on such overpasses is not allowed according to the fire safety requirements, therefore unobstructed apertures are significant noise sources (further referred to as NS).

Figure 2 shows the views of the vehicle overpass on Kanonersky island in St. Petersburg.

a)  b) 

Figure 2. Views of the vehicle overpass on Kanonersky island, St. Petersburg:
a) the vehicle overpass above the playground;
b) the vehicle overpass in a dense residential development

Due to the fact that the real noise sources are oscillatory systems of complex shape, the calculation model uses idealized sound sources of simple shape with the given acoustic power.

The main assumption is that in an acoustically untreated gallery a diffuse sound field is generated instead of the quasi-diffuse sound field considered earlier in works of N. Tyurina [2], where isotropy of the sound occurs, and the intensity of the sound field decreases with the increase of the noise barrier height. In this field the sound is not diffracted through the upper free edge of the noise barrier, but emitted outside through the aperture. The calculation takes into account the sound-absorbing properties of the noise barrier.

The design scheme is shown in Figure 3.

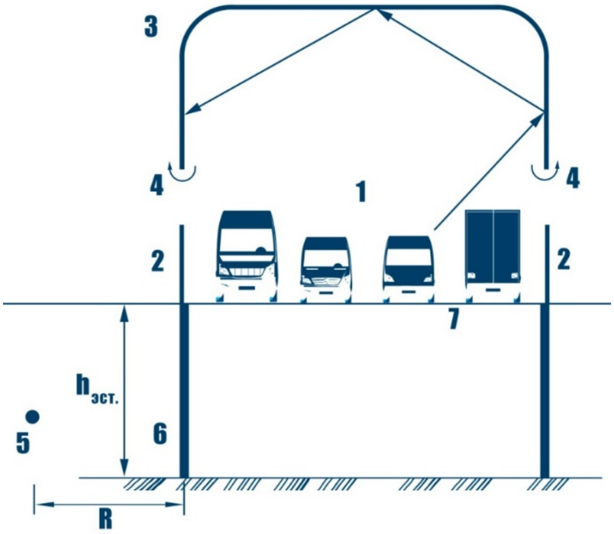

Figure 3. The design scheme of the noise barrier installed in the gallery: 1 – NS, 2 – noise barrier, 3 – acoustically untreated gallery, 4 – aperture, 5 – reference point, 6 – overpasses, 7 – supporting surface

A technical tool, by means of which the derivation of formulas is carried out, is a consistent description of all acoustic processes. In this case, the initial value is considered – the acoustic power of the sound source, and the final value obtained is the intensity of sound, taking into account the change in the sound field when noise barrier is introduced into it.

Acoustic efficiency of the noise barrier is determined:

$$\Delta L_b = 10lg\frac{I_{rp}^{w/ob}}{I_{rp}^{w/b}} \tag{4}$$

where $I_{rp}^{w/ob}$ is the sound intensity in the RP without the noise barrier, W/m^2;

$I_{rp}^{w/b}$ is the sound intensity in the RP with the installed noise barrier, W/m^2;

The intensity of the incident sound on the aperture with the height $h_a^{w/ob}$ without the noise barrier is determined by the following formula:

$$I_i^{w/ob} = \frac{4W_{ns}(1-\overline{a}_a^{w/ob})}{\Psi_v^{w/ob}A_v^{w/ob}}, \text{ W/m}^2 \tag{5}$$

where W_{ns} is the NS acoustic power, W;

$\Psi_v^{w/ob}$ is the coefficient showing the sound field diffusivity level without the installed noise barrier;

$A_v^{w/ob}$ is the equivalent sound absorption area of the equivalent volume without the installed noise barrier, m^2, calculated using the formula (6);

$\overline{a}_a^{w/ob}$ is the average volume sound absorption coefficient without the installed noise barrier, calculated using the formula (7).

$$A_v^{w/ob} = l_b(h_g a_g + b_g a_g + b_g a_s + 2h_a^{w/ob}) \tag{6}$$

where l_b is the length of the installed noise barrier, m;

h_g is the height of the gallery part under the aperture, m;

b_g is the gallery width, m;

a_g is the sound absorption coefficient of the gallery material;

a_s is the sound absorption coefficient of the supporting surface;

$h_a^{w/ob}$ is the height of the aperture without the installed noise barrier, m.

$$\bar{a}_v^{w/ob} = \frac{l_b(h_g a_g + b_g a_g + b_g a_s + 2h_a^{w/ob})}{2l_b(h_g + b_g + h_a^{w/ob})} \quad (7)$$

where l_b, h_g, b_g, a_g, a_s, $h_a^{w/ob}$ are the same as in formula (6).

Acoustic power $W_i^{w/ob}$ of the aperture:

$$W_i^{w/ob} = I_i^{w/ob} l_b h_a^{w/ob}, \text{ W} \quad (8)$$

where $I_i^{w/ob}$ is the intensity of the sound incident on the aperture with the height of $h_a^{w/ob}$ without the noise barrier, calculated using the formula (5), W/m^2;

l_b, $h_a^{w/ob}$ are the same as in formula (6).

The sound intensity $I_{rp}^{w/o\,b}$ in RP without the installed noise barrier:

$$I_{rp}^{w/ob} = \frac{w_a^{w/ob}}{2\pi l_b \sqrt{h_o^2 + R^2}} arctg \frac{l_b}{2\sqrt{h_o^2 + R^2}}, \ W/m^2 \quad (9)$$

where $W_i^{w/o\,b}$ is the acoustic power of the aperture, W, calculated using the formula (8);

l_b is the same as in formula (6);

h_o is the overpass height, m;

R is the distance from the overpass base to the reference point (further referred to as RP), m.

Let us substitute (5), (6) in (9):

$$I_{rp}^{w/ob} = \frac{4W_{ns}(1 - \bar{a}_v^{w/ob}) l_b h_a^{w/ob}}{\Psi_v^{w/ob} A_v^{w/ob} 2\pi l_b \sqrt{h_o^2 + R^2}} arctg \frac{l_b}{2\sqrt{h_o^2 + R^2}}, \ W/m^2 \quad (10)$$

After reductions:

$$I_{rp}^{w/ob} = \frac{4W_{ns}(1 - \bar{a}_v^{w/ob}) h_a^{w/ob}}{\Psi_v^{w/ob} A_v^{w/ob} 2\pi \sqrt{h_o^2 + R^2}} arctg \frac{l_b}{2\sqrt{h_o^2 + R^2}}, \ W/m^2 \quad (11)$$

The intensity of the sound incident on the noise barrier $I_i^{w/b}$, if it is installed:

$$I_i^{w/b} = \frac{4W_{ns}(1 - a_v^{w/b})}{\Psi_v^{w/b} A_v^{w/b}}, \ W/m^2 \quad (12)$$

where W_{ns} is the NS acoustic power, W;

$\Psi_v^{w/b}$ is the coefficient showing the sound field diffusivity level with the installed noise barrier;

$A_v^{w/b}$ is the equivalent sound absorption area of the equivalent volume with the installed noise barrier, m², calculated using the formula (13);

$\bar{\alpha}_v^{w/b}$ is the average volume sound absorption coefficient with the installed noise barrier, calculated using the formula (14).

$$A_v^{w/b} = l_b(h_g a_g + b_g a_g + b_g a_s + 2l_b a_b + 2(h_a^{w/ob} - h_o)) \text{, m}^2 \tag{13}$$

where l_b, h_g, b_g, a_g, a_s, $h_a^{w/ob}$ are the same as in formula (6);

a_b is the noise barrier sound absorption coefficient

h_o is the overpass height, m.

$$a_v^{w/b} = \frac{l_b(2h_g a_g + b_g a_g + b_g a_s + 2(h_a^{w/ob} - h_o))}{2l_b(h_g a_g + b_g + h_b + (h_a^{w/ob} - h_o))}, \tag{14}$$

Where l_b, h_g, b_g, a_g, a_s, $h_a^{w/ob}$, α_b, h_o are the same as in formula (13).

h_b is the noise barrier height, m.

Glass wool, mineral wool and other materials with a high sound absorption coefficient can be used as a sound-absorbing material in the noise barrier design [21–23].

Acoustic power $W_i^{w/b}$ of the aperture:

$$W_i^{w/b} = I_i^{w/b} l_b(h_a^{w/ob} - h_o) \text{, W} \tag{15}$$

where $I_i^{w/b}$ is the intensity of the sound incident on the noise barrier if is installed, calculated using the formula (12), $W/_{m^2}$;

l_b, $h_a^{w/ob}$, h_o are the same as in formula (13).

Sound intensity $I_{rp}^{w/b}$ in the RP:

$$I_{rp}^{w/b} = \frac{W_i^{w/b}}{2\pi l_b\sqrt{(h_o + h_b)^2 + R^2}} arctg \frac{l_b}{2\sqrt{(h_o + h_b)^2 + R^2}}, W/_{m^2} \tag{16}$$

where $W_i^{w/b}$ is the acoustic power of the aperture, W, calculated using the formula (15);

l_b, h_o, h_b are the same as in formulas (14)–(15);

R is the distance from the overpass base to the reference point, m.

Let us substitute (12), (13) in (16):

$$I_{rp}^{w/b} = \frac{4W_{ns}(1 - a_v^{w/b})l_b(h_a^{w/ob} - h_o)}{\Psi_v^{w/b} A_v^{w/b} 2\pi l_b\sqrt{(h_o + h_b)^2 + R^2}} arctg \frac{l_b}{2\sqrt{(h_o + h_b)^2 + R^2}}, W/_{m^2} \tag{17}$$

After reductions:

$$I_{rp}^{w/b} = \frac{4W_{ns}(1 - a_v^{w/b})(h_a^{w/ob} - h_o)}{\Psi_v^{w/b} A_v^{w/b} 2\pi\sqrt{(h_o + h_b)^2 + R^2}} arctg \frac{l_b}{2\sqrt{(h_o + h_b)^2 + R^2}}, W/_{m^2} \tag{18}$$

Thus, substituting (10) and (18) in (4), we will obtain the noise barrier efficiency:

$$\Delta L_{b6} = 10lg\frac{4W_{ns}(1-\overline{a}_v^{w/ob})h_a^{w/ob}\Psi_v^{w/b}A_v^{w/b}2\pi\sqrt{(h_o+h_b)^2+R^2}}{\Psi_v^{w/ob}A_v^{w/ob}2\pi\sqrt{h_o^2+R^2}\,4W_{ns}(1-\overline{a}_v^{w/ob})(h_a^{w/ob}-h_o)}\frac{arctg\dfrac{l_b}{2\sqrt{h_o^2+R^2}}}{arctg\dfrac{l_b}{2\sqrt{(h_o+h_b)^2+R^2}}}, \text{ dB} \quad (19)$$

After reductions and taking the logarithm, we will obtain the following:

$$\begin{aligned}\Delta L_{b6} = {} & 10lg\frac{\sqrt{(h_o+h_b)^2+R^2}}{2\sqrt{h_o^2+R^2}} + 10lg\frac{\Psi_v^{w/b}}{\Psi_v^{w/ob}} + 10lg\frac{(1-\overline{a}_v^{w/b})}{(1-\overline{a}_v^{w/ob})} + 10lg\frac{h_a^{w/ob}}{(h_a^{w/ob}-h_o)} + \\ & +10\lg\frac{l_b(2h_g a_g + b_g a_g + b_g a_s + 2h_b a_b + 2(h_a^{w/ob}-h_o))}{l_b(2h_g a_g + b_g a_g + b_g a_s + 2h_a^{w/ob})} + \\ & +10\lg arctg\frac{l_b}{2\sqrt{h_o^2+R^2}} + arctg\frac{l_b}{2\sqrt{(ho+hb)^2+R^2}}\end{aligned} \quad (20)$$

Assuming that $h_o >> h_b$ we will simplify:

$$\begin{aligned}\Delta L_{b6} = {} & 10lg\frac{\Psi_v^{w/b}}{\Psi_v^{w/ob}} + 10lg\frac{(1-\overline{a}_v^{w/b})}{(1-\overline{a}_v^{w/ob})} + 10lg\frac{h_a^{w/ob}}{(h_a^{w/ob}-h_o)} + \\ & +10\lg\frac{(2h_g a_g + b_g a_g + b_g a_s + 2h_b a_b + 2(h_a^{w/ob}-h_o))}{(2h_g a_g + b_g a_g + b_g a_s + 2h_a^{w/ob})}\end{aligned} \quad (21)$$

3. Results and Discussion

The analysis of the formula (21) showed that noise reduction with the installed noise barrier is determined by two factors:

- decreasing the radiation area of the aperture;
- increasing the sound absorbing properties of the volume when the noise barrier is installed.

The results obtained are extremely important due to their significant difference from the typical approach to the calculation of the noise barrier efficiency in the open space. Thus, the average efficiency of the noise barrier at different heights in the free space can theoretically reach 20 dBA. Under real-life conditions the efficiency of flat barriers does not usually exceed 10–15 dBA due to the additional reflections and finiteness of the noise barrier length. In turn, the efficiency of the noise barriers installed in galleries, in accordance with the results of theoretical calculations according to the derived formula, cannot exceed 6 dBA at different heights, taking into account the sound-absorbing properties of noise-protective structures, which coincides with the average results of experimental studies. Without consideration of the results obtained, greatly inflated values can be calculated while assessing the noise barrier efficiency in galleries. These results commensurate with the noise barriers efficiency in the free field, which will still lead to complaints of the population of the surrounding residential areas about high noise levels despite unreasonably high financial costs.

For different values of the height $h_a^{w/ob}$ and h_b, the ratio in practice can be in the range of 1.3–3, and noise reduction due to the installation of the noise barrier and decrease of the aperture area can reach 1–5 dBA. Analysis of the remaining components of the formula suggests that changing the acoustic properties of the volume increases the acoustic efficiency of the noise barrier by no more than 1–2 dBA. Thus, the noise barrier efficiency will not exceed 2–6 dBA at its different heights.

4. Conclusion

As a result of the study, the following results were obtained:

1. To determine the acoustic efficiency of noise barriers installed at multi-level galleries, an approach based on the main provisions of the statistical theory of acoustics is proposed.

2. A design scheme has been developed to determine the effectiveness of noise barriers in a multilevel gallery

3. The formula for calculating the efficiency of the noise barriers installed in multi-level galleries on the assumption of the approximation of the generated sound field by diffuse one was derived.

4. The main parameters on which the efficiency of the installed noise barriers depends, among which is the decreasing the radiation area of the aperture and the sound absorbing properties of the volume.

5. It has been shown that it is necessary to use absorbing noise barriers in multi-level galleries. The use of reflective noise barriers will not effectively reduce noise due to multiple reflections.

6. The effectiveness of noise barriers installed in multi-level galleries is much less effective in comparison with noise barriers installed in the open space, due to the formation of a diffuse field in a closed volume.

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