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Study of noise originating from selected bridge expansion joints

Badania hałasu pochodzącego od wybranych dylatacji mostowych

Abstract
Road noise constitutes one of the most adverse impacts of road traffic on the environment. Noise that is particularly annoying for local inhabitants is recorded in the vicinity of engineering structures where various types of expansion joints are used [1–3]. There are currently many road connections being built in Poland, including a total of almost ten thousand expansion joints. The authors of this article attempt to determine the noise differences of several of the most commonly used expansion joints – single-, double-, and multi-module, block and finger expansion joint described as one of the most advantageous from the acoustic point of view. This study also attempts to determine the im-pact of expansion joint types on the noise level in comparison to the road section not equipped with these devices, which was adopted as the base noise level.
Keywords: impulse noise, bridge expansion joints, equivalent sound level

Streszczenie
Jednym z najbardziej niekorzystnych oddziaływań ruchu drogowego na otoczenie jest hałas drogowy. Szczególnie dokuczliwy dla mieszkańców hałas notowany jest w pobliżu obiektów inżynierskich, gdzie stosowane są różnego rodzaju dylatacje [1–3]. Obecnie w Polsce wybudowano wiele połączeń drogowych, w ciągu których znajduje się prawie dziesięć tysięcy urządzeń dylatacyjnych. Autorzy artykułu podjęli próbę określenia różnic hałaśliwości dla kilku najczęściej stosowanych dylatacji – szczelnej jedno-, dwu- i wielomodułowej, blokowej oraz określanej jako jednej z najkorzystniejszej z punktu widzenia akustycznego – dylatacji palczastej. W badaniach podjęto również próbę określenia wpływu typów dylatacji na poziom hałasu w porównaniu z odcinkiem drogi niewyposażonym w te urządzenia, który został przyjęty jako bazowy poziom hałasu.
Słowa kluczowe: hałas impulsowy, dylatacje mostowe, równoważny poziom dźwięku

1. Introduction

Poland is one of the countries which, following its accession to the European Union, has observed the dynamic development of the road infrastructure, resulting in the construction of many kilometers of highways, expressways, and related technical and engineering sites. In the vast majority of cases, the connection of the road to a bridge or viaduct is made using a so-called expansion joint gap, enabling the free movement of spans resulting from, for example, differences in air temperatures, which may cause expansion or contraction of the material from which the load-bearing structure is made. From an acoustic point of view, it is the contact between the road and the engineering object that is the most significant place where the so-called impulsive noise phenomenon occurs; it is this noise which is frequently the subject of social disputes [2]. In Poland, the most frequently used types of expansion joints are: tight modular, open finger, bituminous, block, open covered with sheet metal, in the form of a dilatated structure of a platform with continuous surface, the absence of expansion joints in the case of short engineering structures. The type of expansion joint used is determined by the width of coverage, the possibility of longitudinal movements of the span and the sinking of supports, e.g. in areas of underground deposit exploitation, therefore, it is not always possible to choose a specific type of expansion joint. According to the authors' own observations, modular expansion joints seem to be the most frequently used type of expansion joints on engineering structures.

2. Impulse noise phenomenon

The acoustic phenomenon caused by the passage of vehicles over bridge structure expansion joints demonstrates the character of impulse sound. This is not a typical impulse sound, which according to the definition [4–10, 12] means one or more acoustic events of short duration (less than 1 sec) that are of high sound-pressure levels. Noise of this type occurs mainly in the working environment. In the case of the acoustic impact of expansion joints used in bridge structures, the resulting acoustic phenomenon has a slightly different character. Differences in noise amplitudes as they are in the case of other impulse sounds are not as great and the phenomenon itself, although characterised by a short duration, very often causes the excitation of material sound in the structure of the object (especially when using steel elements) of a slightly longer duration. However, sound of this character is very burdensome for people in the affected area. Although it does not exceed the acceptable noise levels in the environment, it may cause significant discomfort and stress and may disturb the sleep of nearby residents' or 'may trigger the onset of sleep disorders for local residents [3].

With regard to impulse noise in industrial scenarios, the most important indicator used in the assessment of workers' exposure to impulse noise is the peak sound pressure level or peak 'C' weighted sound level [7]. When measuring and evaluating road noise with regard to impulse noise from expansion devices, an indicator of the equivalent sound level with 'A' weighting is generally applied, which is then used to compare it with the admissible values.

Usually, although it is not precisely defined in legal regulations in Poland, appropriate correction coefficients are added to the measurement results to account for the share of impulse sound. These are coefficients that increase the results of measurements, so that the impact assessment is more reflects the opinions of residents and the discomfort to which they are exposed. This was confirmed by, among other things, a questionnaire survey performed as part of study [16], the results of which were not discussed in more detail in that article.

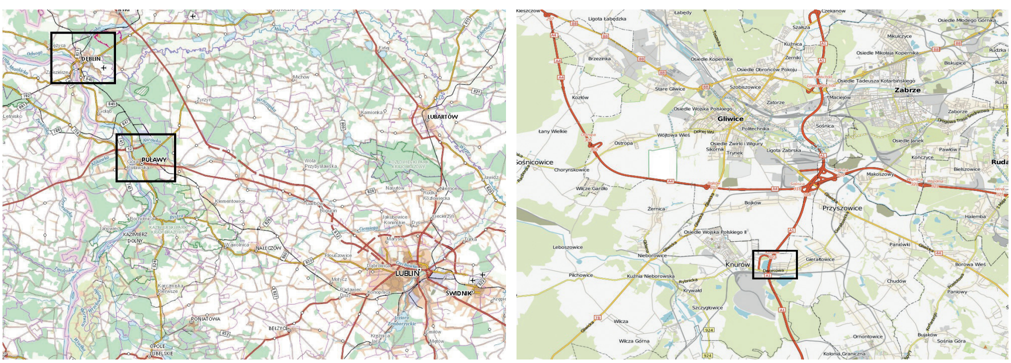
3. Purpose and location of measurements ground

The aim of the study was a comparative analysis of different expansion joint types used in engineering structures with regard to road noise, as well as an attempt to identify noise arising at the interface of the vehicle wheel with the bridge expansion joint. This issue is very important from an acoustic and environmental standpoint because when a car drives on the expansion joint, the impulse noise is created, which should be considered and interpreted in a different manner to road noise.

The scope of analyses included the selection of study sections and the performance of equivalent sound level and noise tests of engineering-structure expansion joints.

The results of the *in situ* study of four bridge structures located in Puławy and Dęblin in the Lubelskie Voivodeship and Knurów in the Śląskie Voivodeship are presented below. As part of the analyses, noise tests, speed measurements of vehicles passing through the expansion joint cross section and measurements of traffic intensity along with the division of the bridges into their generic structures were performed. Such an approach made it possible to verify the level of noise generated by various types of vehicles passing through the gap and also made it possible to attempt to categorise (evaluate) the surveyed bridge expansion joints in terms of their noise levels.

In order to determine the noise level generated during vehicle passage over the object (expansion joint), measurements of traffic parameters and noise on selected test areas were made. Five types of expansion joints were measured: one multi-module expansion joint, two



a) b)

Fig. 1. Location of measurement grounds a) Lubelskie Voivodeship, b) Śląskie Voivodeship

single-module expansion joints, one double-module expansion joint, one finger expansion joint, and one block expansion joint. Four test areas were selected, the first was located along the DK12 national road in Puławy, the second along Marszałka Piłsudskiego Street in Puławy, the third along 15 Pułku Piechoty Street in Dęblin, and the fourth along the A1 Highway in Knurów. Figures 1a and 1b present the detailed location of the testing grounds.

With regard to the standard approach concerning road noise, there is no detailed information available on testing and admissible values for the phenomenon of road impulse noise. The admissible values for traffic noise in the environment were presented in the Regulation of the Minister of Environment from 1st October 2012, Dz.U. Journal of Laws, item 1109. It contains a table listing the admissible levels of environmental noise caused by each group of noise sources. For roads and railways, these values depend on the type of terrain and range from 65 dB for daytime to 56 dB for night time. They do not include the sound pressure level of impulse sources. The impulse correction to the results of impulse parameter measurements can be found in the Regulation of the Minister of the Environment of 30th October 2014, Dz.U. Journal of Laws, item 1542, Appendix no. 8. For the measurement of the equivalent sound level, this correction depends on the type of sound, i.e. whether the sound is highly impulsive, whether the impulse sound has high energy or whether it is a typical impulse sound. These values range from 3 dB to 12 dB, demonstrating that this correction has a significant impact on the final value of the measurement, taking into account the value of the equivalent sound level given in the Dz.U. item 1109.

4. *In situ* measurement and results

After a detailed analysis of the tested sections, ten measurement points, marked PPH-(1-10), were selected:

- PPH-1, PPH-2 – Knurów Highway A1,
- PPH-3, PPH-4 and PPH-5 – DK 12 Puławy-Zwoleń,
- PPH-6, PPH-7 and PPH-8 – Marszałka Piłsudskiego Street in Puławy,
- PPH-9 and PPH-10 – 15 Pułku Piechoty Street in Dęblin.

An example of the measurement point location is shown in Fig. 2.

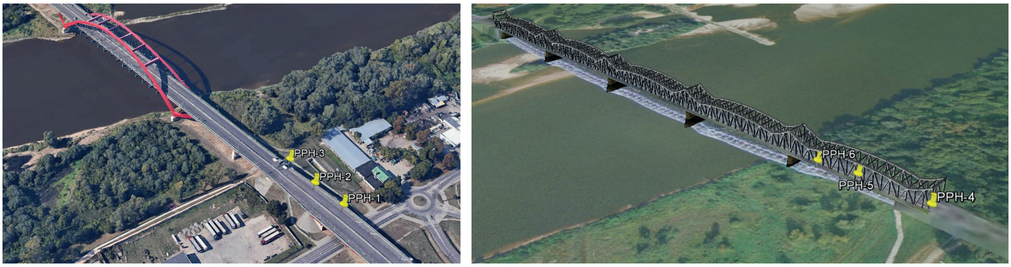


Fig. 2. Location of measurement points PPH-(3-8)

4.1. Methodology of measurement – Puławy and Dęblin

In order to perform noise tests on bridge expansion joints, a study program was first developed which included information on the method of their execution, a list of the measurement equipment used and the organisation of the measurement area [11]. At each measurement point, it was assumed that the microphone of the sound level meter would be mounted 30 cm above the surface of the expansion joint along its axis, on the edge of the road (Fig. 3a). In addition, one measurement point, called the 'base point', was added in each test (Fig. 3b). The base point was located between two expansion joints, at their mid-span. This approach allowed comparison of the sound level from the same source, i.e. a vehicle moving at the same speed, in the same cross section, but without an expansion joint. Over the course of the study, the speeds of passing vehicles were measured, as well as their intensity, along with vehicle classification. In this way, it was possible to read out the noise generated by a single passing vehicle and to perform a comparative analysis of the expansion joint. All surveys were preceded by a field observation and pilot measurements. The measurement equipment which was used for the duration of the study consisted of class 1 sound level meters with the necessary accessories. All meters had the same measurement parameters, i.e. measurement in 1/3 octave bands, FAST constant and correction filter A.

Fig. 3. a) Microphone location above the dilatation b) Microphone location at the base point

An example of how the microphones are arranged relative to each other is shown in Fig. 4. The distance between the base points and the dilatation fluctuated within the range of 30 m.

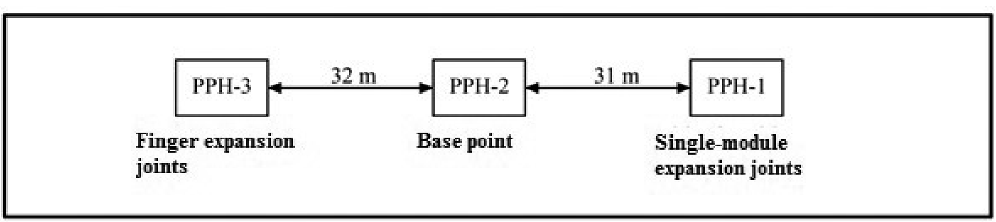


Fig. 4. Scheme of distribution of measurement points on a bridge along the DK12 route Puławy–Zwoleń

4.2. Measurement methodology – Knurów

Noise measurements from the impact of expansion joints used in the WA-470 site on the A1 highway in the town of Knurów were conducted twice: in 2013 [9] and 2018 [13]. In order to perform this, the method of direct measurements within a period of 24 hours was used in accordance with the procedure described in the regulation presented in [15]. These were taken at six points located in the vicinity of the A1 highway in the area immediately adjacent to the bridge structure. The location of the measurement points is shown below in Figs. 5 and 6.

Meteorological conditions were observed and the traffic intensity and speed of vehicles driving on the highway were measured while simultaneously measuring the sound level. Sound level measurements were performed with class 1 precision sound meters, FAST time constant and 'A' weighted characteristics. In 2013, at two points (PDH-2 and PDH-4), the sound level was additionally measured using 1/3 octave filters in order to determine the frequency characteristics of the noise source (identification of the frequency range for sound generated by cars passing over expansion joints used in the site). In 2013, noise measurements at PDH-6, PDH-7 and PDH-8 points were taken within a duration of 30 minutes to obtain data for calibration of the calculation model with which the acoustic modelling was subsequently performed. The results of these measurements are presented in detail in publication [16], and they were not described in more detail as a part of this article.

Fig. 5. Location of measurement points in the vicinity of the WA-470 site in Knurów in 2013

Fig. 6. Location of measurement points in the vicinity of the WA-470 site in Knurów in 2018

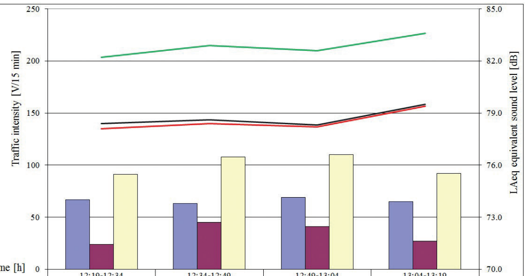
Additionally, in order to check whether the level of noise generated during vehicle movement over the expansion joints is the same for each expansion joint, measurements of noise directly at the wheel of a car moving over the structure were taken in 2013. The measured values of the noise level allowed determining the differences in the noise emission generated during the operation of specific expansion joints.

4.3. Description of performed tests

The study was performed using two approaches which differed in their methods of execution. The first approach concerned measurements in Puławy and Dęblin, the second approach was applied in Knurów on the A1 highway. During the measurement of the sound level (equivalent sound level L_{Aeq}), the speed of the moving vehicle was tested simultaneously with the division into light and heavy vehicles, and the intensity of the moving vehicles was measured, with the division into vehicle type, comprising motorcycles, passenger vehicles, vans, rigid lorries, articulated lorries and buses. The measurements were performed at 15-minute intervals. For each interval, individual groups of vehicles were counted, categorising them into light vehicles and heavy vehicles. Heavy vehicles included rigid lorries, articulated lorries, buses and motorcycles. On this basis, it was possible to calculate the percentage share of heavy vehicles in the traffic flow. Similarly, the speed of moving vehicles was also measured with their division into light vehicles and heavy vehicles. The results obtained for the individual testing sites are described below.

- John Paul II Bridge in Puławy along the national road DK12

Measurements of traffic intensity revealed that passenger vehicles comprised the largest share of vehicle traffic. The share of heavy-duty vehicles was 34.2%. A total of 401 vehicles passed during the 60-minute evaluation. No tractors or bicycles were recorded driving through the site. The average speed of the light vehicles was 76.2 km/h and for heavy vehicles, it was 74.2 km/h. The value of the equivalent sound level for a 15-minute interval was read from each gauge. Figure 7 shows the diagram of traffic intensity in individual time intervals, along with the corresponding value of the equivalent sound level for the single-module expansion joint, the finger joint and the baseline.



Time [h]	12:19-12:34	12:34-12:49	12:49-13:04	13:04-13:19
Traffic intensity (light)	67	63	69	65
Traffic intensity (heavy)	24	45	41	27
Sum of intensities	91	108	110	92
Single-module expansion joint	78.1	78.4	78.2	79.4
Base point	78.4	78.6	78.3	79.5
Finger expansion joint	82.2	82.9	82.6	83.6

Fig. 7. Diagram of traffic intensity together with sound level L_{Aeq} in specific time intervals on the John Paul II bridge as a part of the DK12 route: Puławy–Zwoleń

The John Paul II Bridge was a very important test ground in terms of expansion joint types that were used on the bridge and on the overpass in front of the bridge. Testing at this location made it possible to measure the intensity of sound from the same stream of traffic, moving at the same speeds, passing through two types of expansion joints. Analysing the results presented in Fig. 7, it could be concluded that a single-module expansion joint is quieter than the baseline, which is considered as a reference point. This situation results from the fact that at the measuring point located at the single-module expansion joint, there was an acceleration lane, where vehicles were driving at a distance of 3.5 m further from the meter's microphone than for other measuring points. This had a significant impact on the obtained results.

As previously mentioned in this publication, noise from expansion joints are of an impulse nature. A single pulse of a sound level significantly higher than the average value of the equivalent sound level for the considered time interval (15 minutes) does not significantly increase the average noise level, as interpreted in accordance with the applicable regulations. The authors of the article attempted to identify a frequency band in which impulse noise coming from expansion joint has a higher energy than the reference level – which is the noise generated from the surface of the road rather than from the joint. The aim of this approach

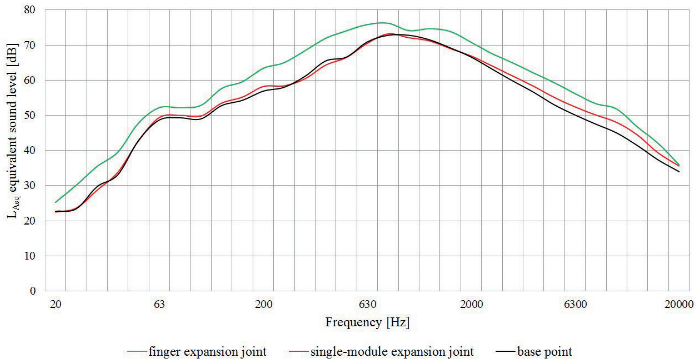


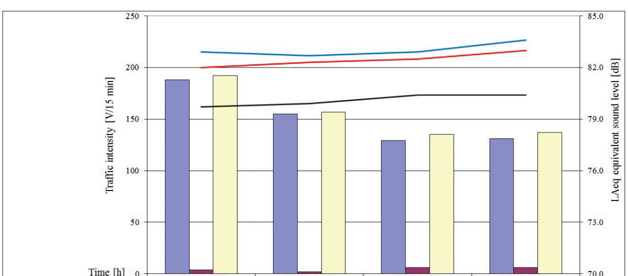
Fig. 8. Comparative analysis of noisiness of finger and single-module expansion joint in the full frequency band compared to the baseline for the study period of 30–45 minutes – John Paul II Bridge in Puławy

was to determine whether the analysed sound level is in the band that could be perceived by the human ear. For this purpose, diagrams were created for each 15-minute measurement, showing the equivalent sound level versus the frequency value, presenting both the expansion joint types, and the baseline (reference level). A sample graph is shown in Fig. 8.

When interpreting the results, one should take note of the expansion joint width as this is a very important parameter. In the case of the finger joint, it was around 75 cm, and for a single-module joint, it was around 7 cm.

- Bridge on Marszałka Piłsudskiego Street in Puławy

In the case of the bridge on Marszałka Piłsudskiego Street, the traffic situation differed significantly in comparison to the John Paul II Bridge. More than 97.1% of vehicles passing through the analysed section of the road were passenger vehicles. During the 60-minute test, a total of 621 vehicles passed; this equated to more than 50% more than on the DK12 national road. This is the result of the structure's location – the entrance to the city centre. As was the case with the John Paul II Bridge, no tractors were recorded passing here. The average speeds



Time [h]	14:13-14:28	14:28-14:43	14:43-14:58	14:58-15:13
Traffic intensity (light)	188	155	129	131
Traffic intensity (heavy)	4	2	6	6
Sum of intensities	192	157	135	137
Single-module expansion joint	82	82.3	82.5	83
Base point	79.7	79.9	80.4	80.4
Double-module expansion joint	82.9	82.7	82.9	83.6

Fig. 9. Diagram of traffic intensity together with sound level L_{Aeq} in specific time intervals on the bridge on Marszałka Piłsudskiego Street in Puławy

of light vehicles were around 48.8 km/h and for heavy vehicles, around 39 km/h. Figure 9 (below) shows traffic intensity during individual time intervals, along with the corresponding value of the equivalent sound level for the single-module expansion joint, the double-module expansion joint, and the baseline.

In this case, analyses were performed across the full frequency band in order to determine the characteristic frequency band for the impulse noise. An example graph for the analysed situation is presented in Fig. 10.

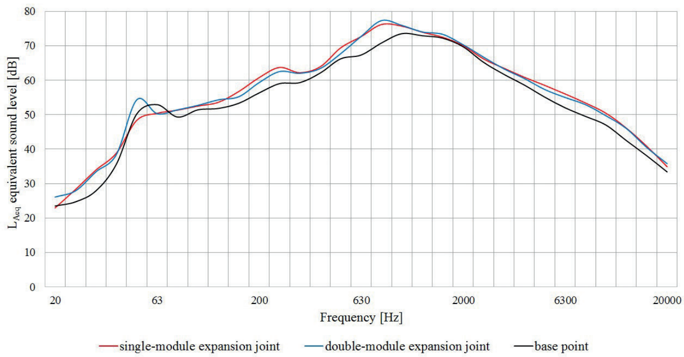
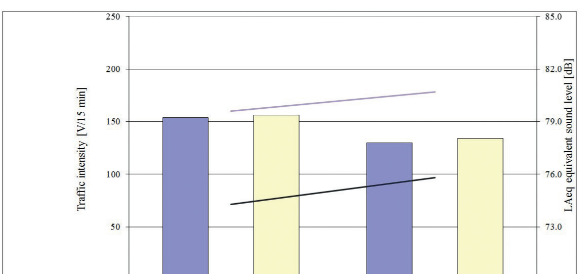


Fig. 10. Comparative analysis of noise of the double-module and single-module expansion joint across the full frequency band compared to the baseline for the study period of 15–30 min – bridge on Marszałka Piłsudskiego Street

The width of the double-module expansion joint was around 12 cm and the width of the single-module expansion joint was around 7 cm.

- Bridge at 15 Pułku Piechoty Street in Dęblin

In the analysed case, the block expansion joint was subjected to noise tests. In the cross section of national road No. 48, passenger vehicles had the largest share of vehicle traffic. Heavy vehicles accounted for only 2.1% of all road vehicles moving on this road. A total of 290 vehicles passed over the analysed section during the 30-minute period of observation.



Time [h]	10:25-10:40	10:40-10:55
Traffic intensity (light)	154	130
Traffic intensity (heavy)	2	4
Sum of intensities	156	134
Block expansion joint	79.6	80.7
Base point	74.3	75.8

Fig. 11. Diagram of traffic intensity together with sound level L_{Aeq} in specific time intervals on the bridge at 15 Pułku Piechoty Street in Dęblin

No tractors or bicycles were recorded during this period. The average speed of light vehicles was 58 km/h and for heavy vehicles, it was 57 km/h. Figure 11 below shows a graph of traffic intensities in relation to the values of equivalent sound levels for the different time intervals. The width of the block expansion joint was 20 cm.

Figure 12 below presents a comparative analysis of block expansion joint noise in relation to the baseline across the full frequency band for the study period of 0–15 min.

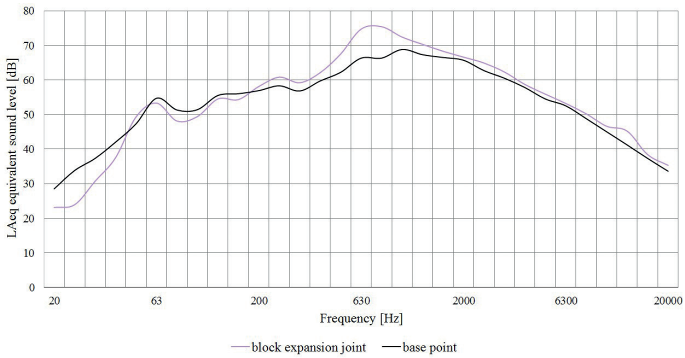


Fig. 12. Comparative analysis of block expansion joint noise compared to baseline across the full frequency band for the study period of 0–15 min – bridge at 15 Pułku Piechoty Street in Dęblin

- Bridge on the A1 highway – Knurów

24-hour noise measurements in the vicinity of the WA-470 site on the A1 highway were performed in 2013 [16] at 6 points. Due to the duration of measurements (24 hours) and the measurement method (direct method) in accordance with the regulation in [15], it was possible to refer directly to the levels of permissible environmental noise [14], which was the main objective of this study. The regulations also characterise the acoustic climate prevailing in the areas adjacent to the analysed site. Table 1 below shows the measurement results.

Table 1. Results of the 24-hour sound level measurements taken in 2013 [16]

Measurement point no.	Sound level (A)	
	Daytime	Night time
PPH-1	74.0	68.6
PDH-1	70.1	65.1
PDH-2	65.8	61.1
PDH-3	60.2	55.5
PDH-4	61.2	56.6
PDH-5	57.8	54.0

Measurements of noise directly at the wheel of a car moving on a highway structure enabled determining the differences in noise emission generated during the operation of particular expansion joints. The obtained average results for individual expansion joints ranged from

106.6 dB to 108.4 dB. It can therefore be concluded that each of the expansion joints had a similar acoustic effect. Additionally, as part of study [16], noise measurements were taken at 1/3 octave frequency divisions. The results of these measurements are presented below in Fig. 13.

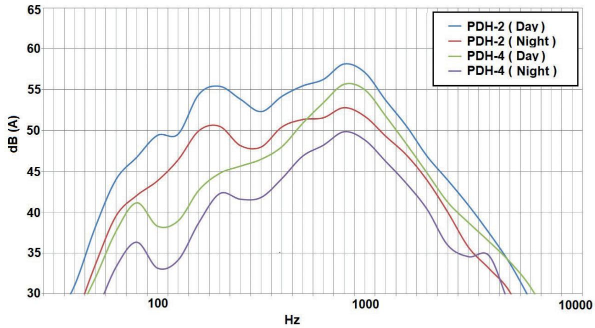


Fig. 13. Summary of frequency characteristics in 1/3 octave centre bands at PDH-2 and PDH-4 sites divided into daytime and night time [16]

In 2018, noise measurements were taken at nine points located in the vicinity of the WA-470 overpass in Knurów [11]. Each of these were measured during four consecutive periods of the day. This allowed additional observation of the noise level variability. These results are presented in Table 2 below.

Table 2. Results of 24-hour sound level measurements taken in 2018 [13]

Measurement point no.	**Sound level (A)**	
	Daytime	Night time
PPH-1	73.9	68.8
	74.3	69.3
	74.0	68.5
	74.5	69.0
PPH-2	69.5	63.7
	69.1	64.5
	69.9	64.3
	70.0	64.7
PDH-1	62.5	55.9
	56.7	54.5
	55.0	52.4
	57.9	53.8

PDH-2	62.5	56.0
	60.0	57.2
	59.9	56.7
	60.2	57.8
PDH-3	62.6	55.8
	60.2	57.0
	59.6	56.1
	59.8	57.2
PDH-4	63.3	56.0
	60.8	56.4
	64.4	59.3
	61.7	58.9
PDH-5	60.0	56.1
	54.7	53.7
	50.4	49.4
	55.3	52.8
PDH-6	59.3	55.6
	52.2	51.0
	49.4	44.2
	54.1	51.2
PDH-7	59.6	50.7
	56.2	54.7
	61.1	56.7
	59.6	57.8

Acoustic modelling was also performed as a part of both studies [13, 16]. The French calculation method 'NMPB-Routes – 96 (SETRA-CERTU-LCPC-CSTB)' was used in noise analysis, as described in 'Arrêté du 5 mai 1995 relatif au bruit des infrastructures routières, Journal Officiel du 10 mai 1995, art. 6' and the French standard 'XPS 31-133'. The view of the geometric part of the calculation model is shown below in Fig. 14. It should be emphasised that in both cases, the noise from car movement over the expansion joint devices was additionally modelled, as presented in Fig. 15. Due to the fact that typical acoustic models do not allow direct representation of this type of noise, in both cases linear sources of industrial noise were used as these best reflected the acoustic impact originating from the expansion joint. The results of the acoustic calculations are presented in Fig. 16 (2013 [16]) and Fig. 17 (2018 [13]).

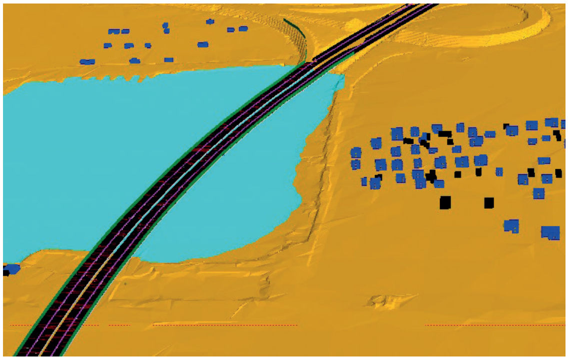


Fig. 14. View of the calculation model (terrain) used in the studies [13, 16]

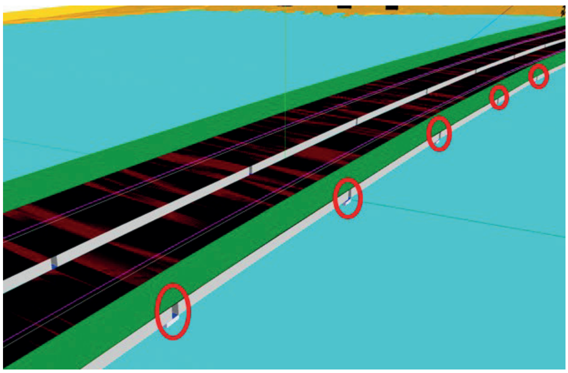


Fig. 15. View of the reflection in the calculation model concerning the acoustic impact of marked expansion joints [13, 16]

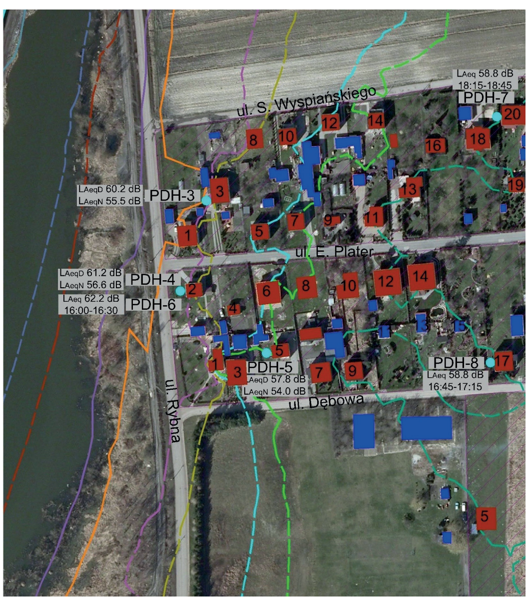


Fig. 16. Results of acoustic calculations performed in 2013 [16]

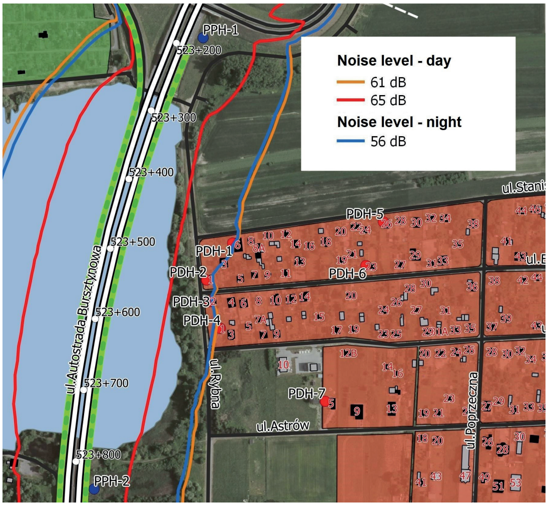


Fig. 17. Results of acoustic calculations performed in 2018 [13]

Specific analysis of measurement and acoustic calculation results is presented in section 5 of the article.

5. Discussion and conclusions

When analysing the results of the expansion joint tests, it is concluded that in each case it is possible to observe a significant difference in relation to the base point in the level of noise generated by the expansion joint in the frequency band of 500–1250 Hz. Noise generated when passing through the expansion joint increases the sound level in this band, which falls within the range of the audible band for humans and can result in a negative impact on humans and the environment. Examples of results indicating this effect are shown in Fig. 18.

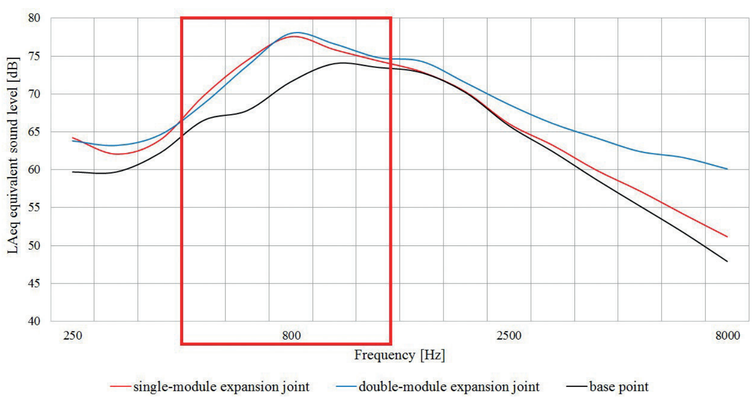


Fig. 18. Analysis in frequency bands for single and double-module expansion joint with reference to the baseline on the bridge on Marszałka Piłsudskiego Street in Puławy

Differences in sound levels are summarised in Fig. 19, in reference to the measured values of the equivalent sound level depending on the baselines for each analysed case. The list does not include point PPH-3 located on the single-module expansion joint on the John Paul II Bridge in Puławy because the measured values of the equivalent sound level are lower due to the greater distance from the noise source than other points.

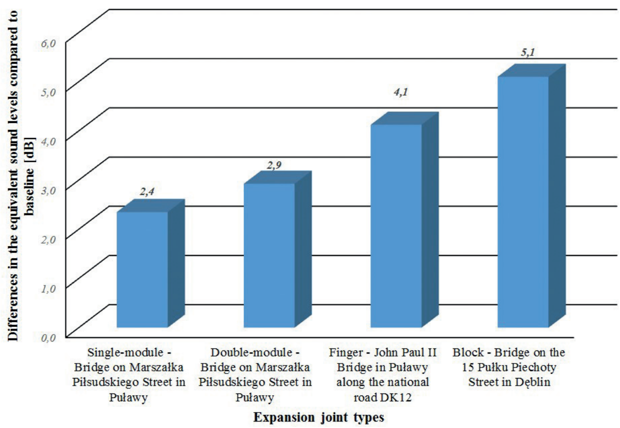


Fig. 19. Differences in the equivalent sound levels for each analysed expansion joint compared to corresponding baselines

Based on the above diagram, it can be concluded that the single-module and double-module expansion joints are the quietest. However, when analysing the obtained values of sound generated when passing over the expansion joint, one should also take note of the technical condition of the expansion joint and its width. Both parameters significantly influence the obtained results. The width of a finger joint is more than 6 times the width of a double-module joint and the sound level difference is only 1.2 dB; therefore, it can be concluded that a finger joint has good acoustic parameters. Nevertheless, based on the performed test, it can be concluded that the block expansion joint is the loudest.

In the area adjacent to the WA-470 site on the A1 highway, the dominant acoustic impact is the noise originating from the passage of vehicles over the expansion joint devices. The nature of this interaction has the characteristics of impulse sound (short duration, high amplitude of noise level), although it is not a typical impulse sound. Because of this, it is much more burdensome for the inhabitants of this area than the typical road noise which is additionally reduced by the noise barriers used on the bridge structure.

It should be noted that the noise levels measured in both 2013 and 2018 are slightly above the limit values at night, mainly at points closer to the analysed overpass. During the daytime, however, there are no instances of exceeding environmental noise limits. The results of measurements performed at the so-called reference points were not compared with the environmental noise limit values due to the fact that they were located in areas not subject to acoustic protection. They were used primarily to observe the parameters of the noise source and to calibrate the calculation model.

When analysing the results of noise measurements, it is necessary to take into account the nature of the acoustic impact that occurs in the studied area and the degree to which it constitutes a nuisance for the residents. Although environmental noise levels are exceeded by small values (less than 3.5 dB) compared to other areas located in the vicinity of main roads in Poland, the nuisance to residents resulting from the impact of vehicle traffic is high. This is due to the participation of impulse sounds originating from expansion joint devices that are additionally amplified by the steel structure of the building and its location above the strong sound-reflecting plane (water surface). Impulse sound, due to its short duration, does not cause a significant increase in the average value of the equivalent sound level, yet is very burdensome for residents, especially at night, under favourable conditions of acoustic propagation. It also certainly causes sleep disruption to people living in the closest vicinity of the highway [3].

When analysing the results of acoustic calculations presented in Figs. 16 and 17, the conclusions drawn from the analysis of noise measurement results should be confirmed. Buildings located closest to the bridge structure are within the range of noise impact that is slightly greater than acceptable. Nevertheless, the residents feel that it is very troublesome, which, as mentioned above, is related to the impulse nature of the sound generated by expansion joint devices. This is confirmed by the results of a survey conducted with residents.

Residents' responses to only one of several questions are presented within this article. This question is: "Is the noise from the overpass on the A1 highway a nuisance?".

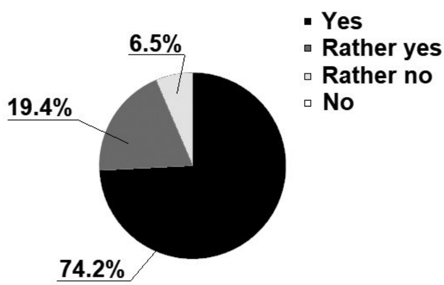


Fig. 20. Summary of residents' answers to the question: "Is the noise from the overpass on the A1 highway a nuisance?"

Residents' responses to the above question confirmed the conclusion formulated on the basis of measurement and calculation results. The majority of residents answered 'yes' and answers 'no' and 'depends on the situation' did not appear at all.

On the analysed WA-470 bridge, a part of the A1 highway, acoustic screens were used to protect residential buildings against the 'typical' impact of noise from vehicle traffic. It should be stressed, however, that the main cause of acoustic nuisance in the studied area is not this type of noise, but noise of an impulse nature, generated by the movement of cars over expansion joint devices, which are not shielded in any way. The effectiveness of the applied acoustic screens is evidenced by the fact that, despite a significant increase in traffic over the last few years, the noise level did not increase significantly. This can be observed by comparing the results of traffic volume measurements and acoustic calculations performed in 2013 and 2018 [13, 16]. Over the last 5 years, the intensity of vehicle traffic has increased by almost 25,000 vehicles per day, and the state of the acoustic climate in the areas adjacent to the analysed overpass did not deteriorate significantly. This can particularly be seen in the comparison of noise measurement results at a point which was located in the same place in 2013 (No. PDH-4) and in 2018 (No. PDH-3). In 2013, a value of 61.2 dB was measured during the daytime and 56.6 dB was measured at night. In 2018, a value of 60.9 dB was measured at daytime and 56.7 dB was measured at night. The remaining measurement results cannot be directly compared because the measuring points were located in different places.

The lack of deterioration of the acoustic condition results from the fact that the acoustic screens used to effectively protect residential areas against the impact of 'typical' road noise and the increase in traffic volume did not have a significant effect upon the acoustic conditions prevailing in the analysed area. However, both in 2013 and 2018, there was significant nuisance present associated with expansion joints which are not protected in any way by the applied acoustic screens, as mentioned above. It is therefore necessary to take measures to mitigate this impact.

In order to achieve mitigation of the impact of expansion joints many types of actions have been considered that may reduce noise that they generate. Such actions may also include the replacement of expansion joint devices, but these are very expensive, and the effect that can be achieved may not provide the expected noise reduction; another option is the use of acoustic screens (which has not been described in detail in this article). The focus, however, is on reducing the noise spread from underneath the structure as this is the most disturbing for the residents. Insulating casing used on the bottom of the structure underneath the expansion joints was suggested in order to achieve this reduction. Acoustic calculations have also been performed which demonstrate the effect of noise reduction after using these casings. It has been concluded that the application of this type of protection will result in the reduction of the equivalent sound level compared to the current state. Due to the fact that these calculations were only performed on the basis of casing manufacturers' catalogue data and did not result from "*in situ*" tests, their results are burdened with a high degree of uncertainty. Because of this, they are not presented in this article.

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