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Experimental studies on the exposure of construction workers to noise emitted by a backhoe loader – a case study

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Abstract Noise is the most commonly existing harmful factor which can be found at workplace. According to the Polish law, an employer is obliged to regularly conduct controls of the working conditions, which include, among others, conducting measurements of harmful factors. Such measurements are usually made after prior arrangements between parties, i.e. the employer and a party conducting the measurements. Therefore, one may suspect justifiably that the conditions in which those measurements are conducted are substantially different from the actual conditions of a particular site. This work includes the presentation of results of measurements of noise emitted by a backhoe loader, which were made both inside the cabin of the operator and in the vicinity of the machine. The measurements were carried out in the course of typical working operations as well as during operation with the use of specialised equipment – e.g. Hydraulic hammer. The results of the measurement show clearly that values of the Highest Permissible Noise Level or Highest Permissible Exposure Limit to which an operator was exposed were in no situation exceeded as long as the cabin door was closed. During work using a hydraulic hammer, people staying near the machine, located at a distance of less than 15 meters, are exposed to noise levels that exceed the permissible values for long-term exposure. However, during work using standard equipment, exceedances of permissible values of noise did not occur.

Keywords: noise measurements, impulse noise, backhoe-loader, standard equipment, hydraulic breaker, construction workers.

1. Introduction

Noise is the most frequently existing harmful factor (nearly 54% of all cases existing in Poland), which can be encountered at working sites [1-3]. Its main source comes from machines and technological equipment used by human beings. The producers of machines and equipment are obliged by proper legal regulations to design their devices in such a manner as to limit the emission of harmful factors to the necessary minimum [4]. This assumption is often difficult and sometimes impossible to meet despite the application of the most recent technical achievements.

Noise as a physical phenomenon may be considered in many ways. There are many criteria to divide the noise aspects, e.g. considering the frequency of the emitted noise, we may analyse the noise in the audible band as well as in the infrasonic and ultrasonic bands. As far as the recorded noise level and the character of change of the noise in time of observation are concerned, we may distinguish three types of noise: steady-state, transient and impulse [5-8].

For each of them, the maximum permissible noise intensities in workplaces were defined [9, 10]. The specificity of noise at the working site as well as the type of performed work requires, above all, the selection of a correct measurement strategy – in accordance with the guidelines set out in the norm PN-EN ISO 9612:2011 [11].

There is a wide range of machines used in construction, which can generally be divided into: machines designed for general work, mainly earthworks (less often reloading); such as: excavators, loaders and the backhoe loader tested in this work. The second group of machines consists of specialised machines – e.g. excavators for demolition work at heights, equipped with equipment with a precisely defined purpose – e.g. hydraulic shears for cutting reinforced concrete, demolition hammers, etc. The last group consists of specialised machines designed for the basics in their entirety to perform precisely defined tasks – e.g. vibratory hammers, piling machines, drilling rigs, etc.

The main sources of noise emitted by construction machines (regardless of their type) include: the drive engine, the hydraulic system and the working equipment, together with the technological processes accompanying their work – cracking/decohesion of materials.

The engines of these machines (most often turbocharged diesel engines) emit broadband noise, mainly low-frequency as well as infrasonic noise caused by the propagation of vibrations generated by the working engine onto the structural elements of the machine. Hydraulic systems are responsible for emitting medium and high-frequency noise, including ultrasonic noise. This is related to the flow of the working medium, especially through valve and control fittings and cavitation that may occur locally. In turn, the specialized work equipment mentioned above generates impulsive noise, often in the form of high-energy impulses.

Much as noise measurements of stationary work stations reflect a danger both for operators as well as other persons present in the vicinity of the workplace, in case of mobile work stands this situation is different, especially if the operator of the machine is operating inside the cabin – just as this is the case for the position of construction machines' operators.

When conducting the noise measurements of the backhoe loader operator's stand, it needs to be considered that the assessment of noise hazard concerns only persons working in this stand. However, noise exposure also includes all persons present in the range of influence of the acoustic source. This is of particular importance if there are persons performing other work in the nearest vicinity of the machine or if they find themselves in this zone sporadically. In such a case, the noise hazard for third persons may be much higher than for the operator, despite a much shorter time of exposure.

There are many publications addressing the influence of noise on the human body. When considering the nature of the influence, we may distinguish: disruptive noise, causing e.g. problems in communication and concentration, and harmful noise, evoking negative changes in the human body [12-19].

Given the effects, these changes may be of a permanent or transitory nature. These include shifting (increasing) of the sensitivity threshold and partial or permanent loss of hearing even in the case of a single occurrence of exposure – especially if high-level impulse noise is in place, e.g. in case of series of shots or explosions and this phenomenon concerns both human beings as animals [20-23].

Among the broad range of machines and devices used in the construction sector, the vast majority of them emit noise, whose levels significantly surpass the values of the Highest Permissible Noise Intensity [NDN] reserved for long-term exposure. Sung Ch. L. and others demonstrated in their work that for the same measuring distance of 15m, 6 out of 23 examined machines emitted noise exceeding 85 dB. Based on the conducted measurements, the most disruptive device turned out to be a pile driving rig, for which the measured noise level amounted to 89.2 dB [24].

In another work, a team managed by Sung Ch. L. showed that pile driving rig, earth auger and loader which are included among machines used for foundation works, emit noise whose instantaneous sound pressure levels exceed 80 dB – in case of pile driving rig up to 100 dB, while the noise is of low-frequency nature, where the highest sound pressure levels were recorded in frequency bands between 160 – 500 Hz. In case of machines used for demolition works, i.e. excavator equipped with a hydraulic hammer, bulldozer and excavator with standard attachment, the measurements showed that in case of operation of a hydraulic hammer the instantaneous sound pressure levels were exceeding 110 dB and in case of the two remaining machines the measurement results were within the range of 80-95 dB. However, the nature of the emitted noise was different in comparison to the foundation-operating machines – the highest sound pressure levels were recorded in frequency bands between 1000 and 5000 Hz, especially for the excavator with a hydraulic hammer attached [25].

In turn, A.H. Suter proved in their work that among 15 different types of construction machines, only in six cases were the recorded noise levels lower than 85 dB. The highest sound pressure levels were recorded for heavy bulldozers – 99 dB. In a situation where machines of similar type and class (size) were compared – e.g. cranes, noise levels lower by 10 dB were recorded for machines with acoustically isolated cabin. Moreover, for machines equipped with a crawler undercarriage, the noise levels emitted by them were higher by 10 dB than this was the case for the same machines but moving on a wheeled undercarriage [26].

The issue of noise emitted by construction machines was also mentioned in work directed by D. Kang [27]. The authors showed that during the measurements of noise emitted by, among others, pile driving rigs, rock-drilling rigs, vibratory hand breakers or breakers, the recorded noise levels exceeded 85 dB, for demolition hammer levels amounting to 101.5 dB were recorded. The authors examined in total of 35 machines and devices of various types (altogether 64 cases), and the noise measurements were made at a distance of 7.5 and 15m from the examined objects. For selected machines, such as e.g. earth augers, the measurements were made for various load conditions of the drive unit. The results indicate that with an increase in the working load, the noise emission rises. For the aforementioned boring rigs, the noise was changing in the scope between 70.8 dB for operation at engine idle speed up to 79.6 dB during drilling.

In the case of construction machines such as backhoe loaders, the noise measurements carried out for the purposes of the product certification process should be made in accordance with recommendations included in the standards: ISO 6393:2008, ISO 6394:2088, ISO 6395:2008 and ISO 6396:2008 [28–31], while one should bear in mind that the measurement conditions described in the standards differ substantially from the ones which are in place in real operation conditions and do not foresee all possible cases/device configurations related to the possible ways of using the machine.

It is also worthwhile to bear in mind that the noise level emitted by backhoe loaders depends on many factors, e.g. general technical condition (wear of components, clearances, etc.), using methods and intensity of works, potential interference in systems or elements of noise suppression and vibration damping (e.g. durable dismantling or damaging of acoustic screens), application of other than standard attachments – demolition hammers with hydraulic drive, sweepers, grubbers, etc.

In their work, Young-Hyun K. and Won-Tae L. proved that the equipping of a backhoe loader with a modified system of flue gas discharge based on a properly perforated exhaust silencer insert reduces the noise, especially in the frequency scope between 1300 Hz to 1500 Hz [32].

Similar conclusions were drawn by T. Olğar in his work. He examined both in analytical, simulating and experimental ways the influence of the configuration of exhaust system elements (inner construction of the silencer) on the level of noise emitted by the machine. The measurement results showed that interference in the exhaust system – especially removal of the original silencer (or replacing it with an incorrect one) causes increase of noise emitted to the environment – on the average by 10 dB across the entire scope of the audible band while the efficiency of the silencer increases along with increase of frequency and reaches its maximum value for the one third octave band of the middle frequency of 12.5 dB – approx. 28 dB [33].

The biggest influence on the levels of noise emitted by machines and devices, apart from interference in the elements of exhausting / drive systems, is also exerted by the application of acoustic screens. These screens may suppress sounds reaching the operator's cabin without simultaneous interference to sounds propagated to the environment, or they can influence both fronts simultaneously. This topic was examined and discussed in the paper where M. C. Özden and M. Özcanli proposed, made and equipped the object of the examination (crawler excavator) with their system of acoustic screens. The screens were installed both in the operator's cabin and in the engine compartment. The influence of the applied screens on the noise levels emitted by the machine was examined. The results showed that after modernisation of the machine, the level of emitted noise dropped by 3-5 dB [34].

In the course of the past years, a tendency for electrification of certain components of the construction machines has been noticed and/or their equipping in systems of recuperation and accumulation of energy originating from the processes taking place within the machine (e.g. recuperation of energy from flue gas). The main objective of such actions is the protection of the environment, reduction of fuel consumption and limitation of emission of harmful gases to the atmosphere. In their work, the team directed by M. de F. Ramos proved that equipping a backhoe loader with a hybrid drive system (electric-combustion) fueling the hydraulic pump allows for saving up to 33% of fuel [35]. As is known, electric engines produce much lower noise than combustion engines of the same power. Given the above, it is assumed that the machines/vehicles of the hybrid drive system are quieter, but research in this scope needs to be conducted in order to verify the given hypothesis.

As it results from the literature review conducted above, the authors were unable to find articles that deal simultaneously with the threat of noise emitted by backhoe loaders in a holistic approach, for both the operator and for people staying near the machine.

Taking all the above into consideration, it is postulated that during the measurement of noise at working stands, such as operators of road and construction machines, not only the exposure of the operator is to be considered but also the influence of noise on the surrounding area and persons that find themselves in this zone and that the tests be conducted for all possible device configurations of the machine.

The articles cited in the introduction above consider the results that were obtained during the measurements of the noise during typical operation of machines and devices, unspecified as to the method of performing the task (working with the front or rear bucket, loading the excavated material, etc.). In addition, the fact of the common use of specialist equipment, e.g. hydraulic demolition hammers, which significantly increases the utility value of backhoe loaders and the versatility of their applications, was also omitted.

The aim of the paper is to determine and compare the acoustic impact of noise emitted by a backhoe loader on both its operator and people present in the vicinity of the operating machine, while taking into account possible operating modes – i.e. waiting for action to be taken (engine idle speed – steady noise), typical work using basic equipment (typical noise in the work environment – intermittent steady/unsteady) and work using specialist equipment – a hydraulic hammer (unsteady noise containing impulsive events).

The results of measurements considering all possible cases, i.e. the types of work performed and the hardware configuration of the machine, are of significant importance for determining the permissible working time of the operator and the permissible time of other employees' stay in the zone of direct exposure to noise, especially in a situation where the work shift is rich in various types of tasks performed alternately for an unspecified duration time.

In the below paper presented the results of measurements of noise emitted by a backhoe loader were presented from both the perspective of health protection of the operator, inside a cabin, but also from the standpoint of persons present in the vicinity of the operating machine for all possible, different operating modes.

2. Methodology

2.1 Object of research

The research focused on the noise emitted by a JCB backhoe loader, model 4CX, produced in 2007. The technical condition of the machine was evaluated as very good. At the time of all measurements, which lasted from March to July 2025, the operating hours counter showed approximately 13,000 hours worked. In the standard case, the machine is equipped with a conventional 4-functional front bucket and standard rear digging bucket. Figure 1a) shows the object of the tests during static noise measurements. Figure 1b) shows the machine during dynamic noise measurements using the standard front attachment – a loader bucket. Figure 1c) shows the machine during dynamic noise measurements when using the standard rear attachment – a digging bucket. Figure 1d) shows the nameplate confirming the positive result of certification tests, informing about the guaranteed sound power level – L_{WA}.

Figure 1. Tested object - JCB 4 CX backhoe loader: during static noise measurements - 1a); during dynamic noise measurements related to the operation of the conventional front attachment - 1b); during dynamic noise measurements related to the operation of the conventional rear attachment - 1c); nameplate informing about the guaranteed sound power level - L_{WA}, as a confirmation of the positive result of certification tests - 1d)

During dynamic tests related to noise measurements using specialized equipment – a demolition hammer, while chiselling reinforced concrete, the machine cooperated with a hydraulically driven hammer from the company BK HAMMER, model BK 680. The hammer was purchased in 2008. The technical condition of the hammer was assessed as good, but the authors could not obtain information about its current number of operating hours. Figure 2a) shows the object of examination with a specialist attachment installed, and Figure 2b) shows an example of a nameplate of an identical hammer to the one which was used during the tests (the original one attached to the device lost its readability). According to the manufacturer's declaration, the noise level (probably A-sound noise level at an unknown distance from the device) is 109 dB [36].

2 b)

Standard Specification						
Model		Unit	BK350	BK450	BK530	BK680
Suitable Excavator		ton	0.8-2.5	1.2-3.0	2.5-4.5	4-7
Operating Weight	Side type	kg	77	99	132	275
	Top type	kg	77	121	148	321
	Box type	kg	113	139	168	325
	Backhoe loader type	kg				305
	Skid Steer Loader type	kg			280	380
Required Oil Flow		l/min	15-30	20-40	25-50	40-70
Setting Pressure		bar	150	150	150	170
Operating pressure		bar	90-120	90-120	90-120	110-140
Impact Energy		Joule	203	271	406	677
Impact Rate		bpm	800-1400	700-1200	600-1100	500-900
Hose Diameter		inch	1/2	1/2	1/2	1/2
Noise level		dB	106	107	109	109

Figure 2. The tested hydraulic hammer attached to the examined backhoe loader under dynamic noise measurement related to the operation of the dedicated rear attachment – 2a); technical data of a hydraulic hammer identical to the one used during dynamic noise measurements [36]

2.2 Measuring equipment

The measurements were carried out with a sound level meter of 2nd class – SVAN 973. The sound level meter enables simultaneous measurements of noise for 3 profiles. For each profile particular measuring parameter may be defined (SPL, LEQ, PEAK, L_{MIN}, L_{MAX}) along with the amplitude-frequency characteristic (A, C, Z/LIN) and time constant (*Slow*, *Fast*, *Impulse*). Apart from operation in the form of a meter, the device may also work simultaneously in octave analyser mode (31.5 Hz÷8kHz) or 1/3 octave mode (20Hz÷10kHz). Aside from the above-mentioned aspects, the meter may also play the role of a personal noise dosimeter. Optionally, recording of the soundtrack is possible in WAV format with sampling frequency 12 or 24 kHz for further processing of the measured signal [37]. The measuring profiles used in the course of the static and dynamic measurements during operation with the use of standard attachments were included in Table 1.

Taking into account the impulse character of noise emitted by an operating hydraulic hammer during the dynamic measurements, including the noise emitted by the specialised attachment cooperating with the examined backhoe loader, for the measuring profiles described in Table 1, the time constant was changed – for each profile „Impulse" time constant was introduced. The remaining acquisition parameters were not changed. Each time, the measurement time lasted 60 seconds.

The authors draw attention to the fact that during noise measurements in the machine environment - environmental noise with particular emphasis on impulsive noise, the ISO 1996-1:2016 [38], ISO 1996-2:2016 [39], ISO 10843:1997 [40] standards apply, as well as the relevant local regulations [41], which contain detailed guidelines related to impulsive noise measurements, defining the criteria and conditions for conducting measurements. The content of Annexe No. 8 of the Regulation [41] referring to the measurements of impulsive environmental noise does not oblige the use of all the provisions contained in Annexe No. 7, especially point E stating the necessity to use specific time constants (as opposed to measurements of typical environmental noise).

It therefore leaves the choice of the time constant for the purpose of measuring environmental noise of an impulsive nature free. However, in the case of noise measurements at workplaces in accordance with the PN-EN ISO 9612:2011 standard [11], the issue of selecting the time constant has been precisely specified. Considering the above and the fact that the criteria based on which noise can be classified as impulsive are unambiguous.

Table 1. Measurement profiles used for static and dynamic measurements for operation with standard attachments – based on [37]

Static and dynamic noise measurements during operation with standard attachments				
Measurement profile number	Measured value	Symbolic designation, calculating formula	Amplitude Correction Curve	Time Weighted Constant
1	Equivalent continuous A-weighted sound pressure level	$L_{pA,eq,Te} = 10\log_{10}\left(\frac{1}{T_e}\int_0^{T_e}\left(\frac{p_{w\tau(t)}}{p_0}\right)^2 dt\right)$, [dB]	A	Slow
2	A-weighted maximum sound pressure level	$L_{A\ max} = 10\log_{10}\left(\max_t\left\{\frac{p^2{}_{w\tau(t)}}{p_0{}^2}\right\}\right)$, [dB]	A	Fast
3	C-weighted peak sound pressure level	$L_{C\ PEAK} = 10\log_{10}\left(\max_t\left\{\frac{p^2{}_{w(t)}}{p_0{}^2}\right\}\right)$, [dB]	C	None

Where: p_0 – pressure of reference; $p_{w\tau(t)}$ – acoustic pressure corrected by selected amplitude-frequency characteristic - w with an appropriately selected time constant - τ; w – the adopted correction characteristic: amplitude-frequency (depending on needs: A, C *or* Z/Lin); τ – the adopted time constant (depending on needs: *Slow*, *Fast* or *Impulse*)

In their work, R. Ordoñez et al. classify as impulsive acoustic events those for which the peak levels – L_{PEAK} are at least 15 dB higher than the equivalent levels – $L_{p,eq}$ in the considered time interval [42]. In turn, in his work, J. N. Fairfax [43], referring to the EEC Directive 79/113 [44], adopts as a criterion for identifying impulsive noise a comparison of the effective values of the sound pressure level corrected by the amplitude characteristic A for two time weighting constants – Impulse and Slow, and in a situation when $L_{pA;Impulse} - L_{pA;Slow} \geq 4$ dB, the noise is considered impulsive.

Taking all the above into account, the authors decided to meet the requirements set out in the above-mentioned standards and regulations at the same time. For this reason, the recorded VA signals were analysed and digitally processed to determine the values of equivalent noise levels using the Slow (S) and Fast (F) time constants recommended by the PN-EN ISO 9612:2011 standard [11], as well as the Impulse (I) time constant defined in the IEC 60651:1979 standard [45], thus emphasizing the particularly negative impact of impulse noise on the human hearing organ. Therefore, the results related to the measurements of the equivalent continuous A-weighted sound pressure level – $L_{A,eq}$ and the A-weighted maximum sound pressure level – $L_{A\ max}$ included in Table 4 (during hydraulic hammer operation) are given in two forms.

2.3 Measurement sequence

The measurements of the noise emitted by the examined backhoe loader were conducted in three measurement sessions. Table 2 contains a description of the measurement structure, divided into measurement sessions and rounds.

In the first session, the noise measurements in stationary mode were conducted – when the machine was still and the engine was working with constant rotational speed – standby / ready for work mode. In the course of the first session, the measurement of noise both inside the operator's cabin, with its door open and closed, and, additionally, in the vicinity of the machine was carried out. The measurements in the vicinity of the machine were conducted at a distance of 3 and 6 m from the external contour of the object of examination, with angle spacing of every 30°, counting from the front of the machine in a clockwise direction (to the right). The measurements were carried out in three rounds for the following engine rotational speeds: 800, 1600, and 2200 RPM. For each measurement round, the following was conducted: two measurements in the operator's cabin, with its door open and closed, two rounds in each measurement point from within the vicinity of the machine located at a distance of 3m from the machine and one measurement in points distant 6m to the machine.

Additionally, apart from determining the most important from the perspective of health and safety, the values of critical parameters used to assess the exposure of a worker to noise, i.e. $L_{pA,eq,Te}$; $L_{A\ MAX,}$ and $L_{C\ peak}$, for the measurements conducted inside the operator's cabin and measurement points located in the vicinity of the machine at a distance of 3m, an analysis of the 1/3 octave bands of the recorded noise was carried out in order to determine its spectral composition. A total of 75 measurements were taken.

Table 2. Structure of measurement realisation sequence

Measurement session	Measurement Round	Measurement sequence	Measurement tour	Number of measurements taken
Static noise measurements - standby mode: source directional characteristics and noise in the operator's cab Date of measurements: 16/04/2024; Weather conditions: air temperature 7°C; moderate wind; heavy cloud cover with local clearings; no precipitation,	Constant crankshaft engine rotational speed equals 800 RPM	Measurements in the operator's cabin	With the cabin door open	2
			With the cabin door closed	2
		Measurements around the machine	At a distance 3 [m] from the machine	14
			At a distance 6 [m] from the machine	7
	Constant crankshaft engine rotational speed equals 1600 RPM	Measurements in the operator's cabin	With the cabin door open	2
			With the cabin door closed	2
		Measurements around the machine	At a distance 3 [m] from the machine	14
			At a distance 6 [m] from the machine	7
	Constant crankshaft engine rotational speed equals 2200 RPM	Measurements in the operator's cabin	With the cabin door open	2
			With the cabin door closed	2
		Measurements around the machine	At a distance 3 [m] from the machine	14
			At a distance 6 [m] from the machine	7
Dynamic noise measurements - implementation of typical work operations using standard equipment Date of measurements 04/06/2024; Weather conditions: air temperature 14°C, light wind; heavy cloud cover; no precipitation,	Working with front attachment - loader bucket, variable engine shaft speed, depending on load	Measurements in the operator's cabin	With the cabin door open	Not applicable
			With the cabin door closed	5
		Measurements around the machine	At a distance ~ 5 [m] from the machine	10
	Working with the rear attachment - digging bucket; variable engine shaft speed, depending on load	Measurements in the operator's cabin	With the cabin door open	Not applicable
			With the cabin door closed	5
		Measurements around the machine	At a distance ~ 5 [m] from the machine	10
	Acoustic background	-	-	5
Dynamic noise measurements - implementation of work operations using dedicated equipment – hydraulic breaker Date of measurements: 02/07/2024; Weather conditions: air temperature 18°C; moderate/light wind; heavy cloud cover; no precipitation.	Working with the dedicated rear attachment – hydraulic breaker, variable engine shaft speed, depending on load	Measurements in the operator's cabin	With the cabin door open	Not applicable
			With the cabin door closed	10
		Measurements around the machine	At a distance ~ 5 [m] from the machine	10
			At a distance ~ 10 [m] from the machine	10
			At a distance ~ 15 [m] from the machine	10
	Acoustic background	-	-	7

In the course of the two following measurement sessions, the dynamic measurements of noise were carried out. The second measurement session concerned the measurements in the course of typical operations, i.e. excavation work and handling of the excavated material with the use of standard attachments. The third measurement session comprised dynamic noise measurements during operation with a specialised attachment – hydraulic hammer (concrete breaking).

During the second measurement session, 10 measurements were taken each time – measurement rounds: inside the operator's cabin during operation with front and rear attachments (cabin door remained closed) and 10 measurements each for operation with front and rear attachments. The measurements were supplemented by measurements of the acoustic background – 5 measurements were made (a total of 45 measurements were taken). Just as this was the case for the majority of stationary measurement (first measurement session), apart from the meter mode, the 1/3 octave analyser was also active for all measurements performed within the second measurement session.

For the third measurement session – operation with hydraulic hammer, 10 measurements were taken each time – measurement rounds: inside the operator's cabin (door closed) and in the vicinity of the machine within a distance of 5, 10 and 15 meters. The measurements were supplemented with acoustic background measurement – 7 measurements were executed (a total of 47 were taken). Just as this was the case during the second measurement session, the 1/3 octave analyser was also constantly active in this case.

3. Measurement results

3.1. Static noise measurement – sound source directionality characteristic

The results of measurements carried out during the 1st measurement session, with the objective to determine the sound source directionality, are included in Table 3.

Table 3. Summary of the results of stationary noise measurements - determination of the directional characteristics of the source, measured in relation to the orientation

Engine crankshaft rotational speed [RPM]	Distance to the measurement point [m]	Measured parameter [dB]	Angle of the directional location of measurement point [°] - measurements in the machine environment							Measurements inside the cabin	
			0	30	60	90	120	150	180	Door open	Door closed
880	3	$L_{A\,Slow,eq,Te}$	65.1	69.0	69.9	70.1	71.7	71.8	71.4	68.0	64.2
		$L_{A\,Fast\,max}$	67.6	79.5	77.5	72.8	82.1	81.7	80.5	75.1	65.3
		$L_{C\,PEAK}$	99.9	97.3	104.8	105.2	106.9	101.9	106.2	98.4	99.0
	6	$L_{A\,Slow,eq,Te}$	67.5	64.8	66.8	68.1	69.3	70.4	67.1	-	-
		$L_{A\,Fast\,max}$	77.9	67.5	76.3	72.7	77.2	80.7	76.4	-	-
		$L_{C\,PEAK}$	93.6	88.0	101.0	93.9	99.8	96.0	100.3	-	-
1600	3	$L_{A\,Slow,eq,Te}$	79.1	72.5	81.9	74.9	77.5	74.5	71.5	72.4	67.9
		$L_{A\,Fast\,max}$	86.9	81.0	87.1	80.0	73.0	82.8	73.1	82.8	73.1
		$L_{C\,PEAK}$	102.1	102.1	106.2	101.7	102.3	98.8	103.9	104.5	95.4
	6	$L_{A\,Slow,eq,Te}$	68.9	71.6	70.7	71.8	69.4	71.4	71.0	-	-
		$L_{A\,Fast\,max}$	72.2	79.2	74.0	80.5	70.9	75.0	75.5	-	-
		$L_{C\,PEAK}$	99.2	102.6	102.8	101.3	105.5	99.0	106.9	-	-
2200	3	$L_{A\,Slow,eq,Te}$	72.6	73.1	81.0	79.6	78.6	76.5	80.5	74.3	68.6
		$L_{A\,Fast\,max}$	82.8	87.8	87.4	85.0	86.7	81.8	71.4	81.8	71.4
		$L_{C\,PEAK}$	104.0	106.7	109.3	105.0	103.3	101.9	108.6	97.1	91.9
	6	$L_{A\,Slow,eq,Te}$	69.7	72.0	81.6	73.1	72.1	70.3	72.0	-	-
		$L_{A\,Fast\,max}$	72.1	73.3	88.4	75.0	74.4	72.0	77.9	-	-
		$L_{C\,PEAK}$	99.8	102.6	105.3	107.6	97.6	107.8	105.7	-	-

The directed angle determining the location of measurement points was measured relatively to the orientation „to the front" of the machine (riding forward) in a clockwise direction. The measurements were performed at points situated on the right side of the machine, given the location of the exhaust pipe on this side, which made it more active, given the emitted noise. The arrangement of measuring points in the machine environment is presented in Figure 3.

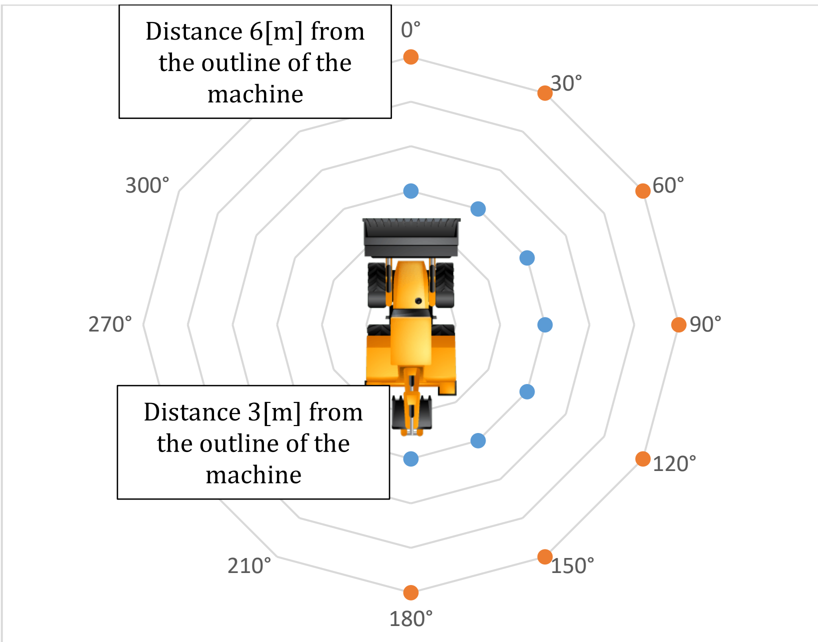

Figure 3. Distribution of measurement points during a session related to static noise measurements

While analysing the data included in Table 3, it can be generally stated that for measurement parameters such as equivalent continuous A-weighted sound pressure level – $L_{pA,eq,Te,}$ along with the increase of rotational speed, the noise emitted by the machine increases as well. This regularity is seen in the case of measurements made in the operator's cabin at door open and closed, as well as in the case of measurements made in the area of the machine, for both assumed measurement distances. The only exception to this rule is a situation where the measurement was taken in a point oriented at the angle of 150° at a distance of 6m, where the sound level was lower for 2200 RPM than for 1600 RPM.

If A-weighted maximum sound pressure level – $L_{A\ max}$ is to be taken into consideration, we may conclude that the highest values of this parameter for the measurement point localised inside the operator's cabin were recorded for engine rotational speed 1600 RPM. If we analyse the values of $L_{A\ max}$ in the vicinity of the machine, we may conclude that for the measurement distance of 3m, no particular regularity can be indicated between the measured values of this parameter in particular measurement points and the engine rotational speed. A similar situation takes place if we analyse results for a measurement distance of 6m.

No clear regularity can be indicated for C-weighted peak sound pressure level – $L_{C\ PEAK}$ parameter when it comes to the relation between the measured values of $L_{C\ PEAK}$ and rotational speed – in particular for points orientated at the angle of 90° and more – for measurements carried out at a distance of 3m from the outline of the machine. In a situation where the measurements were taken in points located in front and at angles of 30° and 60°, the values of $L_{C\ PEAK}$ were increasing along with the increase of the rotational speed. No particular regularity can be indicated between the values of $L_{C\ PEAK}$ obtained in measurement points located at a distance of 6m from the outline of the machine and the engine rotational speed for any measurement point or direction.

However, when it comes to the values of this parameter recorded in the operator's cabin, the same regularity as in case of $L_{A\ max}$ values can be noticed, i.e. the highest values of $L_{C\ PEAK}$ were measured at the engine rotational speed of 1600 RPM in a situation when the operator's cabin door was open. On the other hand, when the cabin door was closed, the highest values were recorded at the engine rotational speed of 880 RPM.

As it results from the data presented in the above Table 4, both during operation with the front and rear attachments, higher noise levels are noted in the vicinity of the machine and lower noise levels are measured in the operator's cabin during operation of the rear attachment. It is suspected that it is related to the orientation of the measuring microphone, directed to the operator's sight (the measurements during the operation of the front attachment were directed towards the engine). This regularity is also valid for measurements made in the vicinity of the machine; operation with the use of the front attachment is louder.

3.2. Dynamic noise measurements – operation of standard attachments

The results of measurements made in the course of a second measurement session – noise dynamics during operation with the use of standard attachments were included in Table 4.

Table 4. Summary of dynamic noise measurement results – work with standard attachments

Measured Parameter	Assessment criterion	Noise measurements – operation with the front attachment		Noise measurements – operation with the rear attachment	
		Operator's cabin	Machine environment	Operator's cabin	Machine environment
$L_{A\ Slow,eq\ Te}$	Max	74.6	76.7	70.7	80.7
	AVG	**72.4**	**75.4**	**70.4**	**77.4**
	Min	69.1	73.5	70.0	74.1
$L_{A\ Fast\ max}$	Max	91.1	98.6	87.3	93.4
	AVG	**85.0**	**93.0**	**81.6**	**87.7**
	Min	76.8	88.5	73.4	76.3
$L_{C\ PEAK}$	Max	110.0	111.9	104.2	109.1
	AVG	**106.3**	**109.1**	**102.7**	**103.8**
	Min	102.8	105.5	100.5	98.6

In all measurement cases related to the type of performed operation (front / rear attachment) and location of measurements (cabin/vicinity), no surpassing of the Highest Permissible Noise Intensity was noted for the parameters such as A-weighted maximum sound pressure level – $L_{A\ max}$ (115 dB) and C-weighted peak sound pressure level – $L_{C\ PEAK}$ (135 dB) – neither for average nor maximum values of these parameters.

The values of equivalent continuous A-weighted sound pressure level – $L_{pA,eq,Te}$ do not surpass either the permitted value reserved for the exposure lasting 8 hours for work performers inside the operator's cabin, i.e. direct control cabin deprived of telephone communication -75 dB. The same applies to the related working stands located in the area of the operating backhoe loader (e.g. operator's assistant) for which the permissible by law equivalent continuous A-weighted sound pressure level related to an 8-hour working day – $L_{pA,eq,8h}$ should not surpass 85 dB [10]. Therefore, neither the operator nor persons staying in the area of the operating machine are exposed to a daily noise exposure level – $L_{EX,8h}$ would surpass 75 or 85 dB (depending on the considered working stand). Work of the operator and third persons in the vicinity of the backhoe loader is possible in overtime without the necessity of the application of ear protectors. Nevertheless, the maximum working time permitted by law for third persons in the vicinity of the operating backhoe loader is increased in a wider scope than is the case for the working time of the operator.

3.3. Dynamic noise measurement – operation with the use of dedicated attachment: demolition hydraulic hammer/breaker

The results of measurement conducted in the course of the 3rd measurement session, i.e. dynamic measurement of noise during operation with the use specialist attachment in the form of a demolition hammer with the hydraulic drive system, were included in Table 5.

Basing on the data shown in Table 5 it may be concluded that (similarly to noise measurements during operation with standard attachments, both in the vicinity of the machine and operator's cabin) the noise measured in operator's cabin did not surpass the Highest Permissible Noise Intensity for parameters such as A-weighted maximum sound pressure level – $L_{A\ max}$ and C-weighted peak sound pressure level – $L_{C\ PEAK}$. This statement is true both for average values and for maximum values of these parameters from the singular measurements.

Nevertheless, in accordance with provisions of the Polish law, the permissible equivalent level of sound on the operator's stand, i.e. "*…inside cabins of direct control without telephone connection…*", should not exceed 75 dB [10]. This is of particular importance due to the specificity of the operator's work manifested in the necessity of maintaining constant attention and sight focusing on the object of operation (bucket, hydraulic hammer, etc.) while simultaneously manipulating the on-board instruments such as control levers in order to perform the operational functions.

In accordance with data included in Table 5, there are transgressions of permissible values of equivalent continuous A-weighted sound pressure level – $L_{A,eq,Te}$ reserved for an 8-hour working day. Given the above, the work of a person employed at the backhoe loader operator's post is not possible in full work time scope without the necessity to use ear protectors, under the additional obvious condition that the work is performed with the cabin door closed. Otherwise, this working time is reduced to a much greater extent than in a situation when the operator is in a closed cabin.

Table 5. Summary of results of dynamic noise measurements – operation with the use of hydraulic breaker

Measured Parameter	Assessment criterion	Operator's cabin	Machine environment		
			Distance 5m	Distance 10m	Distance 15m
$L_{A,eq,Te}$ */***	Max	77.0/82.6	93.6/99.2	90.0/95.6	87.1/92.7
	AVG	**73.8/79.4**	**92.0/97.6**	**87.4/93.0**	**84.2/89.8**
	Min	68.8/74.4	91.1/96.7	83.2/88.8	81.5/87.1
$L_{A\,max}$ **/***	Max	90.3/93.9	103.3/106.9	100.2/103.8	96.9/100.5
	AVG	**86.8/90.4**	**101.3/104.9**	**97.7/101.3**	**93.5/97.1**
	Min	75.7/79.3	98.6/102.2	94.1/97.7	91.1/94.7
$L_{C\,PEAK}$ ****	Max	125.3	119.2	116.5	112.6
	AVG	**117.8**	**118.0**	**114.2**	**110.1**
	Min	109.4	116.5	109.5	109.0

* - calculated with *Slow* Time Weighting;
** - calculated with *Fast* Time Weighting;
*** - calculated with *Impulse* Time Weighting;
**** - calculated without Time Weighting;

As this was the case in the course of operation with standard attachments and noise measurements inside the cabin during operation with hydraulic hammer, no transgressions of the values of the Highest Permissible Noise Intensity for $L_{A\,max}$ or $L_{C\,PEAK}$ were recorded in any of measurement point located in the vicinity of the machine in this case. However, when it comes to exposure to noise of workers of the construction industry who stay in direct vicinity of the machine, it should be borne in mind that the measured values of the equivalent continuous A-weighted sound pressure level – $L_{A,eq,Te}$ exceed the permissible value reserved for 8-hour exposure (85 dB). Due to the above, the presence within the area of acoustic exposure should be reduced. The permissible exposure time in a situation where a worker remains in the zone of direct exposure and is not equipped with ear protectors can be determined based on the following relation:

$$T_{e,permissible} = T_0 \cdot 10^{\left(\frac{L_{EX,8h} - L_{A,eq,Te\,Measured}}{10}\right)} \tag{1}$$

Where: $T_{e,\,permissible.}$ – maximum permissible noise exposure time (calculative) for which the measured equivalent continuous A-weighted sound pressure level – $L_{A,eq,Te\,Measured}$ is equal to X [dB];
T_0 – reference time, T_0 = 8[h] = 480 [min];
$L_{EX,8h}$ – Highest Permissible Noise Intensity of a daily level of exposure to noise, $L_{EX,8h}$ = 85 [dB];
$L_{A,eq,Te\,Measured}$ – measured value of equivalent level of A-sound [dB] for the exposure time equal T_e;
T_e – real exposure time in [min].

After substituting the above formula with the corresponding data, the maximum measured unitary values of $L_{A,eq,Te,\,Measured,}$ the permissible time of exposure to noise originating from the hydraulic hammer for workers within the vicinity of the machine amounts to:

- 18.25 minutes, when the worker stays at a distance of 5 meters,
- 41.8 minutes, when the worker stays at a distance of 10 meters,
- 81.5 minutes, when the worker stays at a distance of 15 meters.

As shown based on the conducted measurements, it is the assisting workers, staying in the vicinity of a backhoe loader, who are exposed to noise emitted by the machine to a much greater extent than its operator.

Comparing the data included in Table 5 with data from Table 4 it may be concluded that operation with a hydraulic hammer generates noise whose equivalent continuous A-weighted sound pressure level – $L_{A,eq,Te}$ is, on average, higher by 9 dB than operation with an excavating attachment and by 7 dB higher in comparison to the loading attachment. Operation with a demolition hammer is responsible for the emission of higher A-weighted maximum sound pressure level – $L_{A\,max}$ and C-weighted peak sound pressure level – $L_{C\,PEAK}$, whose values are higher by respectively: 8.8 dB in comparison to operation with excavating bucket (rear attachment) and 5.4 dB for operation with loading bucket (front attachment) for A-weighted maximum sound pressure level – $L_{A\,max}$ and 15.1 dB in relations to operation with excavating bucket and 11.5 dB for operation with loading bucket when comparing the values of C-weighted peak sound pressure level – $L_{C\,PEAK}$.

3.4. Measurements of the acoustic background

It is indispensable to mention the acoustic background when measuring noise at a workstation. The average results of measurements of the acoustic background split into second and third measuring sessions have been summarised in Table 6.

Table 6. Summary of background noise measurement results

Measured Parameter	Assessment criterion	Acoustic background measurements	
		2nd measurement session – standard attachment operation	3rd measurement session – hydraulic hammer operation
$L_{A\ Slow,eq,Te}$	Max	48.9	71.4
	AVG	**44.2**	**69.1**
	Min	38.7	60.0
$L_{A\ Fast\ max}$	Max	66.1	86.5
	AVG	**60.3**	**81.4**
	Min	50.5	72.5
$L_{C\ PEAK}$	Max	93.1	100.3
	AVG	**87.1**	**94.1**
	Min	75.3	84.8

As can be proved based on the data included in Table 6, after comparing the values included in it with values included in Tables 4 and 5, in all of the examined measurement cases, a distance from the acoustic background preferred by the provisions of law, not smaller than 10 dB, was kept. Given the above, there is no need to apply adequate modifying corrections.

In case of measurements taken in the vicinity of the machine, the acoustic background distance in the course of the 2nd measurement session (i.e. dynamic noise measurements during typical operations with use of standard attachments) was not smaller than 24.6 dB. In the course of the 3rd measurement session (i.e. dynamic noise measurements during operation with use of specialist attachment – hydraulic hammer) was no smaller than 15.7 dB.

While analysing the data provided in Table 5, significant differences in sound levels of the acoustic background can be noticed for both measurement sessions. This is due to atmospheric conditions in place at the time. For this reason, it is recommended in the course of carrying out noise measurements in an open area to, upon possibility, verify as frequently as possible the distance of the acoustic background in such a way to be able to correspondingly react to measurements burdened with error and to modify their values by corrections or to reject them.

Considering remarks above, all the conducted noise measurements can be considered correct and representative. The above presentation of results intends to signal to the reader and to make them aware of the fact that the exposure of operators of construction machines and the remaining workers of the construction sector strongly depends on the type of machine and the currently applied attachment. An objection or remarks of a reader may be brought by the quality of execution of the measurements, manifesting itself in a significant value of the measurement uncertainty of the B type. This is due to a limited number of measurement repetitions. The authors are fully aware that for a correct statistical conclusion, the number of measurements should have been significantly increased, for each of the above-described cases, up to at least 30.

By operating in such a way, the time needed to take measurements would have been increased several-fold, which would imply severe problems of a technical and organisational nature. Due to the unconditional necessity of maintaining the continuity of the production process within the facility – open-pit mine of mineral resources (aggregates), taking as many measurements in just three measurement sessions (i.e. 3 days of measurements lasting 8 hours) was technically impossible and costs of potential renting of a machine for such a period significant. Nevertheless, such a procedure would undoubtedly turn into a reduction of measurement uncertainty and, along with it, into an increase in the quality of the conducted measurements.

4. Conclusions

Based on the conducted analysis, we may conclude the following:

1) The operator's cabin is an efficient barrier for noise coming from outside. Although significant differences were noted between the noise level inside the operator's cabin generated during operation with the use of various attachments (not higher than 10 dB), still, no Highest Permissible Noise

Intensity value was surpassed. One should bear in mind that the above conclusion is binding only while the operator's cabin is closed. It was also shown that door opening during operation causes a significant increase in the noise level inside the cabin, by approximately. 3 dB during the idle run of the machine. In no analysed case was a transgression of the Highest Permissible Noise noted.

2) Based on the measurements made in the course of a stationery operation mode, we may state that:
   a. The machine generates higher noise levels in the lateral axis direction in comparison to the longitudinal axis (from the side). An increase in the rotational speed of the engine generates higher noise levels.
   b. The highest noise levels in the vicinity of the machine were noted in a measurement point oriented at an angle of 60° to the front side of the machine.
   c. Opening of the operator's cabin door causes a significant increase in the noise level inside the cabin, reaching even 9.3 dB (correction with characteristic A) with the engine working at a speed of 2200 RPM.
   d. C-weighting curve shows high sensitivity to external factors, which for singular measurements gives results different from expected at particular measurement points. This happens, e.g. when the measured sound level is higher in a measurement point located twice as far as a point located in the same direction but placed closer to the source of sound. Analysing the source of this phenomenon would require conducting a series of measurements at every measurement point. The reason for this could be the low-frequency sounds and characteristic points of these waves – measurement in the node/antinode of the wave.
   e. A regularity where the point of the lowest exposure to noise, placed at the angle of 0° - located in front of the machine - is generally kept (noise suppression caused by the construction elements of the machine – front loading bucket). The relatively highest exposure to noise was noted in measurement points located at the side of the backhoe loader. Based on the obtained measurement results, it cannot be clearly stated whether the front zone (30°-90° from the front side of the machine) or the rear zone (90°-150°) of the measurement area was more exposed to noise.
   f. No transgressions of the Highest Permissible Noise Intensity were noted even when the highest rotational speed was put in place for the purposes of the measurements.
3) Dynamic operation mode – front and rear attachments:
   a. Differences in sound level during operation with standard front and rear attachments are noticeable. Lower sound levels were recorded in the operator's cabin in a situation when the operator was using the rear attachment – digging bucket. In case of measurements executed in the vicinity of the machine, higher levels of A-weighted maximum sound pressure level – $L_{A\ max}$ and C-weighted peak sound pressure level – $L_{C\ peak}$ were measured during operation of the front attachment – loading bucket.
   b. Both in the operator's cabin and in the vicinity of the machine, no transgressions of the Highest Permissible Noise Intensity were noted.
   c. A decrease of sound level is noticeable in octave/one-third octave bands from 66.3 dB (for 1250 Hz) to 59.5 dB (for 5000 Hz), i.e. for the scope of the highest sensitivity of the human's hearing, where the difference comes to 6.8 dB when we consider operation with the front attachment. A corresponding difference for operation with the rear attachment comes to 11.8 dB (67.0 dB for 1250 Hz and 55.2 dB for 5000 Hz). Based on the above, we may conclude that the nuisance caused by operation with the rear attachment is smaller. On the other hand, the mean logarithmic values of the sound levels are similar (64.0 dB for operation with the rear attachment and 63.4 dB for operation with the front attachment), which makes, that basing on the obtained measurements it is difficult to conclude on the scope of comparison between the acoustic nuisance produced by one attachment or another.
4) Hydraulic hammer
   a. Operation with a hydraulic hammer generates noise, whose spectrum is of entirely different character to the one noticed in spectra related to operation with the loading (front) and digging (rear) attachments. The spectrum of noise produced during hammering shows a strong growing tendency for sound levels in frequency scopes from 31.5 to 1000 Hz (increase of the noise level by 49 dB). Subsequent stabilisation of the noise levels is noticed at a very high level, approaching maximum levels for the entire spectrum. This phenomenon takes place especially in the scope of the highest sensitivity of the human hearing, after which, in the frequency band of 8000 Hz, a significant decrease of the recorded sound level is noticed. We may therefore conclude that the hydraulic hammer generates noise which is particularly nuisance.

b. The measurement results of operation with a hydraulic hammer give higher values of sound levels in frequency scopes covering the scope of the highest sensitivity of human hearing. Analysis of the values of linear levels of acoustic pressure in the scope of low frequencies allows us to state that high sound levels are related to the operation of the demolishing hammer. Moreover, the measurements in the operator's cabin show definitely higher values of linear levels in octaves/one-third octaves of low frequencies, especially when the cabin door is closed. We may, therefore, suspect that the closed cabin has some properties of a soundbox.
c. The noise levels recorded during operation of the hydraulic hammering the operator's cabin differ substantially from the values measured during operation of the front and rear attachments – the difference reaches nearly 10 dB. From the operator's cabin perspective, the operation with a demolishing hammer generates higher noise levels in bands 31.5, 2000 and 4000 Hz. These frequencies are probably related to the local resonance of the supporting structure and the cabin.
d. Operation with a hydraulic hammer generates noise whose levels cause transgression of the Highest Permissible Noise Intensity. Given the above, the persons remaining for any reason in the direct vicinity of the machine should be equipped with ear protectors, and the time of their work near the machine should be duly reduced.

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Additional information

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