DOI: 10.36137/2014E

INSTYTUT KOLEJNICTWA

ISSN 0552-2145 (print) ISSN 2544-9451 (on-line)

Environmental Impacts of High-Speed Rail. Part 2: Vibrations

Krzysztof POLAK[1]

Summary

This article describes issues related to the environmental impact of vibrations generated by high-speed rail. It indicates the most important legal regulations concerning the impact of vibrations on buildings and people in the buildings as well as the main sources of vibrations generated by high-speed rail. The negative impact of vibrations on various elements of the environment (people, buildings, animals) in the stage of construction, operation and decommissioning of high-speed rail is determined. The most common ways of minimising that type of impact are outlined.

Keywords: vibrations, high-speed rail, environmental impact of high-speed rail

1. Introduction

The first part of the series of articles on the impact of high-speed rail on the environment described issues related to the acoustic impact generated by high-speed rail [1]. The most important legal regulations concerning noise in rail transport were indicated and the main sources of noise generated by high-speed rail were determined. Negative acoustic impacts on various elements of the environment at each stage of high-speed rail operation were outlined, and the most frequently used mitigating solutions were characterised.

The second part is an attempt to characterise the most important issues associated with the impact of vibrations on the environment resulting from the operation of high-speed rail. It discusses the most important legal regulations on the impact of vibrations, the sources of their formation and ways of minimising them.

2. Environmental vibration impact assessment in legislation

European countries generally do not have comprehensive legislation regulating rail transport vibration emissions. The available documents, which are based on a number of national and international standards, only define procedures and assessment of vibration emissions generated by a line and railway vehicle [2].

At the European level, the issues of limiting the negative impact of vibrations from rail transport are laconically defined in Directive 2016/797 of the Commission of the European Parliament and of the Council (EU) of 11 May 2016 on the interoperability of the rail system within the European Unio [3]. That document only indicates that the operation of the railway system must not exceed the unacceptable level of ground vibrations in the vicinity of the infrastructure.

In Polish legislation, general provisions relating to the emission of environmental pollutants, including vibrations, are set out in the Environmental Protection Law [4]. That act specifies the necessity to incur the costs of removing the effects of environmental pollution by the entity causing it and also imposes an obligation on the entity undertaking such activities (the negative impact on the environment of which is not yet recognised) to take all possible measures to minimise that impact.

National legislation also specifies requirements associated with the construction of new buildings in the vicinity of railway lines, indirectly defining the scope of the zone of impact of railway vibrations on the environment. Those issues are contained in the Act on Railway Transport [5] and the implementing act – the Regulation of the Minister of Infrastructure of 7 August 2008 on the distance requirements and conditions allowing the location of trees and shrubs, acoustic protection elements and execution of groundworks in the vicinity of railway lines, as well as the manner

---

[1] Ph.D.; Railway Research Institute, Railway Track and Operation Department; e-mail: Kpolak@ikolej.pl.

of arranging and maintaining snow screens and firebreaks [6].

It follows from the provisions of those acts that structures and buildings may be located at a distance of not less than 10 m from the border of the railway area, however, the distance from the axis of the outermost track must not be less than 20 m, with the exception of structures and buildings intended for managing railway traffic, maintaining the railway line and transporting people and goods.

The need to take the impact of vibrations into account also results from the provisions of the Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions to be fulfilled by buildings and their locations [7]. The document [7] states that (...) *a building with rooms intended for human occupation should be erected outside the range of dangers and nuisances specified in separate provisions, while erection of buildings within such range is permitted on condition that technical measures are applied to reduce the nuisance below the level specified in the provisions or increase the resistance of the building to the dangers and nuisances, if this is not inconsistent with the conditions established for areas of limited use, specified in separate provisions* (...). The above-mentioned nuisances include vibrations (vibration).

The Regulation also determines the requirements for vibrations coming into a building from outside (e.g. from a railway line); a building should be located in places least exposed to noise and vibrations. Where vibrations exceed acceptable levels, effective safeguards must be implemented [7]. Additionally, buildings with rooms requiring protection from external vibration should be located at appropriate distances from the sources of the nuisance, adequately positioned and shaped, the rooms should be arranged in a rational way and vibration-absorbing elements should be used [8].

The most important principles and criteria for assessing the impact of vibrations on buildings and people in the buildings, as well as guidelines for the performance of measurements and analyses to evaluate the level of vibrations, are set out in two Polish standards:

- PN-B-02170:2016: Evaluation of harmfulness of vibrations transmitted by the ground to buildings [9],
- PN-B-02171:2017: Evaluation of vibrations influence on people in buildings [10].

The above standards are referred to by the provisions of the Regulation7, described earlier in this section, which clearly indicates that the assessment of the impact of vibrations on buildings and people in the buildings should be carried out in accordance with the mentioned documents [11].

The PN-B-02170:2016 [9] standard provides for two ways of assessing the effect of vibrations on the building structure:

- full assessment, which can be applied to any type of building,
- an approximate assessment, which is only applicable to the most common building classes.

To carry out a full assessment, it is necessary to:

- make a building model for dynamic calculations,
- assume the kinematic force by means of measured or predicted vibrations of the foundations,
- carry out calculations of the dynamic forces acting additionally on the building structure as a result of vibrations,
- verify the strength of individual elements of the building structure or their equivalent strength [12].

In the case of buildings made of prefabricated elements (large slabs, large blocks), having no more than 5 overground storeys, and buildings made of elements intended for manual laying (bricks, hollow blocks), an approximate assessment may be used. This is based on the determination of the so-called dynamic influences scale (SWD):

- SDW-I – applied to buildings of compact shape with external floor plan dimensions not exceeding 15 m and with one or two storeys, none of which exceed any of the floor plan dimensions,
- SWD-II – applicable to buildings up to 5 storeys whose height is less than twice the smallest width of the building, as well as to buildings up to 2 storeys, which do not meet the conditions specified for SWD-I [12, 13].

The standard [9] also defines the conditions for omitting the assessment of the effect of vibrations on the building structure if the amplitude of the horizontal ground motion accelerations at the site of the building foundation meets the following condition:

$$a_p \leq 0{,}05 \tag{1}$$

where: a_p – peak ground acceleration constituting the kinematic damping of the building [m/s^2].

Based on relation (1), it is assumed that the impact of vibrations on the building may be neglected in design calculations if it is located at a distance greater than 25 m from the railway track axis. The above condition refers only to the effect of this factor on the building structure. It does not take into account the effects of vibrations on the people in these buildings or on sensitive equipment (e.g. servers) [8].

The assessment of the effect of vibrations on people in buildings is defined by the standard [10]. It defines permissible vibration values to ensure the required comfort under various occupancy conditions in living quarters, workshops, offices and special-purpose rooms (e.g. hospitals). The standard introduces two methods by which the effects of vibrations on people in buildings are to be determined. Both methods involve assessing vibrations in the 1/3-octave frequency bands from 1 Hz to 80 Hz [14, 15].

The first method of assessing the effect of vibrations on people in buildings is based on measuring the corrected value of the vibration acceleration (or velocity) over the entire frequency band. Correction involves introducing a correction filter into the measurement track, resulting in a corrected RMS of the acceleration (or speed). The standard [10] defines the human perceptibility threshold for this parameter, the value of which, equal to the acceleration along the *z*-axis (along the spine axis), is 0.005 m/s^2, whereas along the *x and y* axes (i.e. perpendicular to the spine axis) it is 0.00036 m/s^2. While relatively simple, this method is information-poor. Even if the permissible human vibration thresholds are exceeded for people in buildings, no information is obtained about the frequency band in which the exceedance occurred, making it impossible to select appropriate vibration reduction solutions [16].

Another method specified in the standard [10] is the *Root Mean Square (RMS)* spectrum of the vibration acceleration (or speed). To assess the human vibration comfort, it is necessary to use the corresponding nomograms, which are expressed in a coordinate system (independently for the vertical *z*-direction and the horizontal directions: *x, y*):

- vertical axis: RMS of the acceleration (velocity) amplitude,
- horizontal axis: vibration frequency.

The lowest polygonal line should be regarded as the human vibration perception threshold. Vibration values below that line are considered not perceptible for humans, while values above it correspond to a multiple of the perceptibility threshold. The most common way to carry out this assessment is to plot the results for the individual frequencies of the middle terce bands as bars on nomograms. Below is an example of a graph comparing the results of the RMS spectrum method with the permissible levels (Fig. 1).

3. Main sources of vibrations

Many factors influence the level of vibrations (and their frequency) generated during high-speed rail vehicle travel. The most important ones are the technical condition of the vehicle, its speed, the type and condition of the surface, the substrate (ground), as well as the distance and location of the structures affected by vibrations, the structure's type and condition and the type of anti-vibration protection used [18].

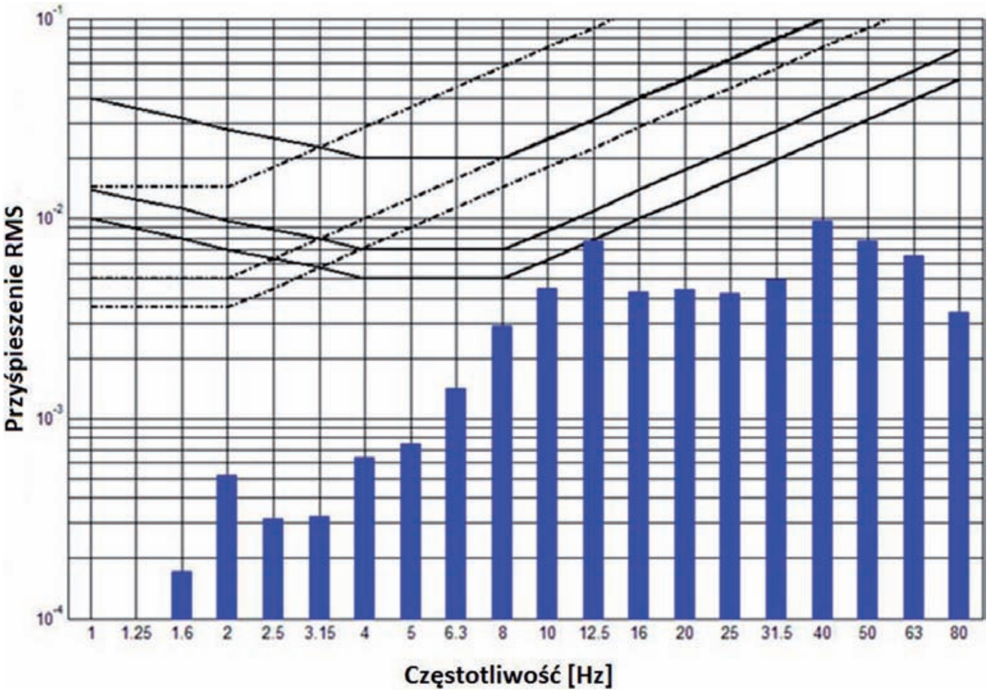

Fig. 1. Example result of vibration assessment by the RMS spectrum method [17]

The sources of vibration from a passing railway vehicle may include auxiliary equipment, compressors (including air-conditioning compressors), unbalanced rotating masses of vehicle rotating components (engine rotor) [19], and the overhead contact line (as a result of interaction with the pantograph) [20]. However, the most important vibration source responsible for the negative impact on buildings and the people inside is dynamic phenomena, defined as time-varying force excitations at the wheel-rail interface [21].

For phenomena occurring at the wheel-rail interface, we can distinguish three main factors generating these vibration processes:

- dynamic interactions depending on the unevenness of the running surfaces,
- transmission of quasi-static loads on individual wheelsets at the point of contact along the track,
- wheel and/or rail running surface irregularities (e.g. rail joints, turnouts, crossings, flat spots, tread build-up [22].

Additional vibration amplification factors at the rolling surface contact point occur on the horizontal curve of the track and are due to momentary lateral forces. There are three main mechanisms for inducing additional vibration:

- lateral influences between the top of the rail head and the wheel running surface,
- wheel flange friction against the lateral part of the rail head,
- longitudinal displacement due to varying sliding of the wheel and rail running surfaces [23].

All these phenomena generate vibrations in the low and medium frequency bands. The vibration generated by a railway vehicle is a function of its speed and the wavelength of the irregularity, which is then emitted as a wave through the track to the environment [19]. The specific effects of vibration from railway vehicles are mainly characterized in terms of Rayleigh and Love surface waves [24–26].

The longitudinal waves (Love waves) propagate at a significant speed which causes them to fade rapidly as the distance increases. In contrast, containing both vertical and radial components of motion, a Rayleigh wave is characterised by a combination of longitudinal compression and dilation, as well as an elliptical displacement of the surface in the vertical plane in the direction of wave propagation. Due to their low velocity and high energy, Rayleigh waves diminish in proportion to the square root of the distance. This type of surface wave, carrying about 70% of the energy of the whole wave, is the main factor in the vibrations transmitted to the environment [19, 27, 28].

4. Effects of vibrations on people and buildings

Rail transport vibration is caused by human activity. The following aspects should be considered when determining the effect of vibrations on a building or the people in it:

- the source (type, frequency of occurrence),
- the propagation path (substrate type, distance, propagation path),
- the mode of vibration reception (exposure time, direction of reception, contact phenomena),
- vibration impact assessment (vibration dose, permissible thresholds) [14].

The analysis of the impact of vibrations received by buildings and the people inside them should also include a set of survey information criteria relating to the elements under study. It is worth analysing whether the vibrations are controlled or dependent and examining their continuity and regularity, the exposure duration, the frequency bands and amplitudes, as well as the characteristics of the vibration source and the structure (technical condition, foundation method, dynamic properties, distribution of bracing) [14].

As mentioned in earlier chapters, the level of vibration nuisance depends on many factors. The individual perception of each individual must also be considered when assessing the impact of vibration. Notably, vibrations may adversely affect not only people and structures but also animals [29]. Thus, such an assessment should also consider the impact on fauna, by identifying local population structures or the state of the natural environment. The impact of construction work and high-speed rail vibrations on animals can be compared to acoustic impacts, which are described in [1].

The impact analysis for a high-speed railway line should cover the construction, operation and decommissioning phases [1].

In the construction phase, the negative impact of vibrations will be connected mainly with the work of heavy equipment (construction machines) and the transport of construction materials and raw materials. The level of noise nuisance near the railway line and access roads will vary greatly and be more noticeable near the interchange (station), engineering structure and other construction sites, as well as near construction site camps and machine operation areas. Construction work may cause discomfort among nearby residents and wildlife; however, any such nuisance would be temporary, effectively ceasing once the project is completed. Without a detailed analysis of all the factors influencing the magnitude of vibration emissions (e.g. number and type of construction machinery, operating time, technical condition, characteristics of the nearest buildings), it is impossible to accurately predict vibrations during the construction phase. The same applies to any nearby buildings. The lack of knowledge of all the parameters makes it impossible to identify the impacts. Nonetheless, the studies conducted so far allow us to conclude that, in most cases, the impact of vibrations transmitted by the ground to the building can be neglected if it is located more than 20 m away from the source of vibrations caused by construction work [8].

At the operational stage, the vibration nuisance will be related to the movement of high-speed railway vehicles. The input data used to develop the vibration propagation model will enable the impacts on buildings and the people in them to be identified in detail. Buildings near the high-speed railway line will be exposed to negative vibration impacts (much like the people inside them). The results of railway vibration measurements in various buildings indicate that, in most cases, excessive effects of vibrations on people inside them can occur up to a distance of about 50 m from the railway track [30].

Human exposure to vibrations can cause negative functional (short-term effects) and pathological (long-term) effects. These depend on many vibration parameters, including amplitude, frequency, exposure time, human characteristics (age, gender, health status) and the type of vibration isolation used. Fig. 2 shows the most important effects of vibration on humans.

In the case of functional effects, most symptoms pass when the vibration stimulus ceases to have an effect or is reduced below the individual tolerance threshold [19].

To assess the effects of vibration on buildings, normative regulations [9] define damage zones, which are based on a frequency-dependent plot of acceleration amplitude [13]. The standard sets out five damage zones with the following types of damage [13, 31, 32]:

- Zone I – vibrations with no effect on the building.
- Zone II – vibrations affecting the building's finishing elements (coatings, plaster). These vibrations cause accelerated technical wear and tear on the building but are not detrimental to its load-bearing structure. This is the lower threshold for hairline and larger cracks in structural elements.
- Zone III – vibrations detrimental to the building's load-bearing structure, causing localised hairline and larger cracks in structural and building elements. Coatings and plaster may fall off. This is the lower threshold of severe building damage, affecting the strength of individual structural elements of the building.
- Zone IV – vibrations highly damaging to the building, causing numerous cracks and local damage, including damage to masonry and other individual structural and building elements. It poses a risk to the safety of the building's users.
- Zone V – vibrations causing a risk of construction disaster.

According to the standard [9], a building's technical safety is ensured if the lower limit for the formation of hairline and larger cracks in structural elements is not exceeded (Zone II).

The decommissioning phase of the high-speed rail lines is bound to be associated with similar vibration impacts as the construction phase. This is because such work will be carried out using similar construction machinery.

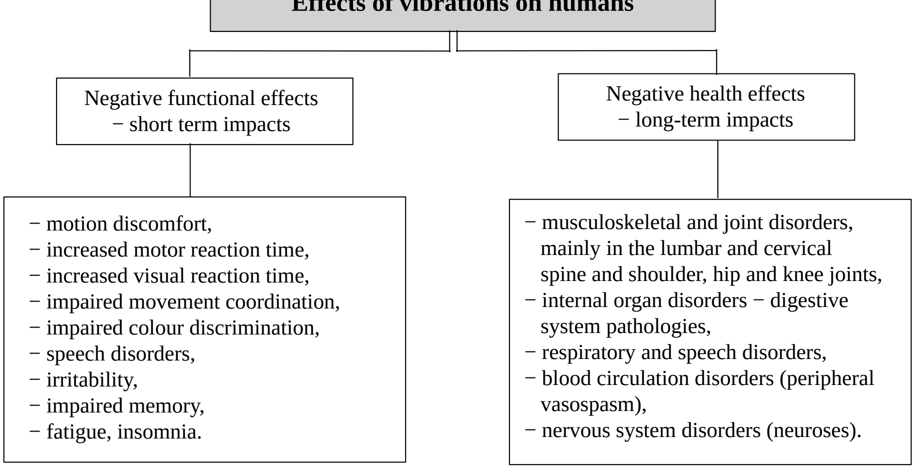

Fig. 2. Effects of vibration on humans: own elaboration based on [19]

5. Solutions to minimise the impact of vibrations on buildings and people

One important aspect related to the impact of vibrations on buildings and people is the use of appropriate minimisation solutions. It must be emphasised that using just any vibration isolation will not have the desired effect of reducing vibration levels. Not only may poorly selected vibration isolation prove ineffective, but it may also increase vibration levels around the railway line. It is therefore important to design effective vibration mitigation solutions before applying them. An analysis of the effectiveness of vibration isolation, its parameters (stiffness, thickness, damping), ground conditions, the condition and design of the track superstructure, as well as the distance from buildings and their design, will make it possible to select the optimal solutions [30]. Mitigation solutions for high-speed rail vibrations can be broken down into three phases: construction, operation and decommissioning.

During the project implementation/decommissioning phase, the negative impacts can be reduced by:

- appropriate planning of construction work near buildings exposed to excessive vibrations (e.g. by limiting work to daytime),
- setting up construction camps and access roads in areas where they will be less of a nuisance to people and animals,
- using modern and efficient construction equipment in good working order,
- regularly inspecting and maintaining construction machinery,
- optimising the use of construction equipment and means of transport (minimising unnecessary trips, limiting idling of machinery, etc.).

During the operational phase, active protection, i.e. reducing vibration emissions at the source, is most often used to minimise the negative impact of vibration. It involves installing vibration isolation in the track superstructure, including:

- under-ballast or under-slab vibration isolation mats,
- vibration isolation pads, under-ballast pads, under-block pads,
- elastic rail clips,
- rail pads,
- rail joint bars using rail profiles [33–40].

Further, solutions to minimise vibrations at the source are also used on high-speed railway vehicles. The most commonly used measures to mitigate vehicle vibrations include:

- improving the wheel rolling surface (roundness),
- reducing unsprung mass,
- introducing sprung mass [41–44].

If active protection (at the source) is impossible, solutions are applied along the vibration propagation route or directly at the structure at risk (passive protection). The most commonly used propagation route solutions are anti-vibration screens/baffles installed in the ground. This entails placing a material into the ground which, due to its properties (density, stiffness), can absorb vibrations from the surrounding soil [45–49].

Passive protection of buildings at risk involves the application of vibration isolation to the entire structure or individual elements. The most commonly used solutions include:

- vibration isolation mats,
- elastomeric vibration isolators,
- air-cushion isolators [50].

In the case of new buildings, priority should be given to erecting them in areas where the applicable vibration levels are not exceeded. Newly designed buildings should incorporate state-of-the-art techniques and the anti-vibration protection described so that the vibrations to which the building will be exposed do not exceed acceptable thresholds and do not pose a risk to the occupants.

6. Conclusion

The entire transport system, including high-speed rail, has always been accompanied by dynamic impacts that transfer vibrations to the environment. The need to minimise their negative effects on buildings and the people in them has led to the development of complex vibration isolation systems that limit the propagation of vibrations. Preparing a proper design and selecting the right solutions is impossible without accurate and detailed identification of the effects of vibrations generated by high-speed rail.

This article aims to provide an overview of the vibration impacts generated by high-speed rail. It discusses the most important legal regulations concerning vibrations in railway transport and characterises their main sources. Further, it attempts to determine the negative impact of vibrations on buildings and the people inside them, as well as on the natural environment near high-speed railways, including the local fauna. Lastly, it presents the main solutions used to minimise the negative impact of vibrations on the analysed elements of the surroundings and natural environment.

References

1. Polak K.: *Environmental Impacts of High-Speed Rail, Part 1: Acoustic Impacts*, Problemy Kolejnictwa, 2023, vol. 200, pp. 209–216.

2. Ouakka S., Verlinden O., Kouroussis G.: *Railway ground vibration and mitigation measures: benchmarking of best practices*, Railway Engineering Science, 2022, No. 30.
3. Directive (EU) 2016/797 of the European Parliament and of the Council of 11 May 2016 on the interoperability of the rail system within the European Union (OJ L 138, 26.5.2016).
4. Environmental Protection Law of 21 April 2001 – consolidated text of Dz.U. /Journal of Laws/ of 2016, item 672.
5. Act of 28 March 2003 on railway transport (consolidated text of Dz.U. /Journal of Laws/ of 2024, item 697).
6. Regulation of the Minister of Infrastructure of 7 August 2008 on the distance requirements and conditions allowing the location of trees and shrubs, acoustic protection elements and execution of groundworks in the vicinity of railway lines, as well as the manner of arranging and maintaining snow screens and firebreaks (consolidated text of Dz.U. /Journal of Laws/ of 2008 No. 153, item 955).
7. Regulation of the Minister of Infrastructure of 12 April 2002 on the technical conditions which must be fulfilled by buildings and their locations (Dz.U. /Journal of Laws/ of 2019, item 1065, as amended).
8. Stypuła K., Kozioł K.: *Wpływ drgań na projektowanie budynków* [The impact of vibrations on building design], Nauka i Budownictwo, 2016, R.20, No. 12, pp. 98–102.
9. PN-B-02170:2016-12: Ocena szkodliwości drgań przekazywanych przez podłoże na budynki [Evaluation of the harmfulness of buildings vibrations due to ground motion].
10. PN-B-02171:2017-06: Ocena wpływu drgań na ludzi w budynkach [Evaluation of vibrations influence on humans in buildings].
11. Stypuła K.: *Praktyczne aspekty stosowania zasad ochrony środowiska przed drganiami w procesie przygotowania i realizacji inwestycji kolejowych* [Practical aspects of applying the principles of environmental protection against vibrations in the process of preparing and implementing railway investments], Przegląd Komunikacyjny, 2019, No. 8, pp. 2–7.
12. Stypuła K., Kozioł K.: *Stosowanie pomiarów drgań i obliczeń symulacyjnych w ramach ochrony sąsiedniej zabudowy przed drganiami kolejowymi* [Application of vibration measurements and forecasting calculations in the framework of protection of neighborhood buildings against railway vibrations], Zeszyty Naukowo-Techniczne Stowarzyszenia Inżynierów i Techników Komunikacji w Krakowie, 2019, vol. 2(119), pp. 235–246.
13. Bukała M. et. al.: *Analysis of rail traffic vibrations' impact on a residential building. A case study*, Engineering Expert, 2021, No. 1, pp. 35–49.
14. Korzeb J.: *Predykcja wybranych oddziaływań dynamicznych w strefie wpływu infrastruktury transportowej* [Prediction of selected dynamic impacts in the impact zone of transport infrastructure], Prace Naukowe Politechniki Warszawskiej, seria Transport, Warsaw, 2013, vol. 9.
15. Kawecki J., Stypuła K.: *Projektowanie budynków z uwzględnieniem wpływu drgań komunikacyjnych na ludzi w budynkach* [Designing buildings taking into account the impact of traffic vibrations on people in buildings], Fizyka budowli w teorii i praktyce, 2009, vol. IV, pp. 69–74.
16. Kawecki J., Kowalska A.: *Analysis of influence of vibrations on humans in buildings in standards approach*, Archives of Civil Engineering, 2012, vol. 58, No. 2, pp. 223–239.
17. Kowalska-Koczwara A., Pachla F., Tatara T.: *Measurements of Human Perception of Train Vibration*. Applied Sciences, 2024, vol. 14(8):3404.
18. Pachla F. et.all.: *Optymalizacja zabezpieczeń przed drganiami kolejowymi na przykładzie nastawni w Białej Rawskiej* [Optimization of protection against railway vibrations on the example of the signal box in Biała Rawska], Przegląd Komunikacyjny, 2017, R. 72 No. 6, pp. 2–8.
19. Nader M.: *Modelowanie i symulacja oddziaływania drgań pojazdów na organizm człowieka* [Modeling and simulation of the impact of vehicle vibrations on the human body], Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw 2001.
20. Kuznietsov V., Rojek A., Szulc W.: *Opracowanie algorytmu systemu antykradzieżowego sieci jezdnej w transporcie szynowym* [Development of an algorithm for an anti-theft system for the rail transport contact line], Problemy Kolejnictwa, 2023, vol. 199, pp. 17–25.
21. Nowakowski T., Staśkiewicz T.: *Wpływ balastowania torowiska na drgania parasejsmiczne w eksploatacji infrastruktury tramwajowej* [The influence of track ballasting on paraseismic vibrations in the operation of tram infrastructure], Problemy Kolejnictwa, vol. 172, pp. 47–54.
22. Kouroussis G., Connolly D.P., Verlinden O.: *Railway-induced ground vibrations – a review of vehicle effects*, International Journal of Rail Transportation, 2014, No. 2(2).
23. Thompson D. J., Jones C. J., Gautier P.E.: *Railway noise and vibration: mechanisms, modelling and means of control*, Elsevier, 2009.
24. Kisilowski J.: *O niektórych źródłach wibracji i hałasu w układzie pojazd szynowy – tor* [On some sources of vibration and noise in the rail vehicle-track system], Liga Walki z Hałasem, Warsaw, 1994.
25. Connolly D.P. et. al.: *Benchmarking railway vibrations – Track, vehicle, ground and building effects, Construction and Building Materials*, 2015, vol. 92, pp. 64–81.
26. Korzeb J.: *Analiza drgań komunikacyjnych z zastosowaniem teorii falek* [Analysis of traffic vibrations

using wavelet theory], Prace Naukowe Politechniki Warszawskiej, 2011, No. 77.

27. Ciesielski, R., Kawecki J., Maciąg E.: *Ocena wpływu wibracji na budowle i ludzi w budynkach – Diagnostyka Dynamiczna* [Assessment of the impact of vibrations on buildings and people in buildings – Dynamic Diagnostics], Instytut Techniki Budowlanej, 1993.
28. Connolly D.P., Forde M. C.: *Use of Conventional Site Investigation Parameters to Calculate Critical Velocity of Trains from Rayleigh Waves*, Transportation Research Record, 2015, No. 2476, pp. 32–36.
29. Milewicz J., Mokrzan D., Szymański G.M.: *Environmental Impact Evaluation as a Key Element in Ensuring Sustainable Development of Rail Transport*, Sustainability, 2023, No. 15, 13754.
30. Stypuła K., Bohatkiewicz J.: *Zagadnienia ochrony środowiska w procesach inwestycyjnych* [Environmental protection issues in investment processes], TTS Technika Transportu Szynowego, 2013, vol. R.20, No. 2–3, pp. 4–10.
31. Chrzan T.: *Wpływ eliptycznego rozkładu radialnej sejsmicznej prędkości drgań na bezpieczeństwo budynku* [The influence of elliptical distribution of radial seismic vibration velocity on building safety], Nauka w Budownictwie, Wybrane Problemy, 2023, No. 5, pp. 14–17.
32. Jakubczyk-Gałczyńska A.: *Ocena wpływu drgań komunikacyjnych na budynki za pomocą maszynowego uczenia* [Assessing the impact of traffic vibrations on buildings using machine learning], Nauka w Budownictwie, Wybrane Problemy, 2023, No. 11, pp. 6–9.
33. Costa P.A. et. al.: *Ballast mats for the reduction of railway traffic vibrations*, Earthquake Engineering and Soil Dynamics, 2012, vol. 42, pp. 137–150.
34. Ma M. et. al.: *An experimental study of vibration reduction of a ballasted ladder track*, Proceedings of the Institution of Mechanical Engineers, Part F, 2017, vol. 231, pp. 1035–1047.
35. He C. et. al.: *An efficient prediction model for vibrations induced by underground railway traffic and experimental validation*, Transportation Geotechnics, 2021, vol. 31:100646.
36. He W. et. al.: *Environmental noise and vibration characteristics of rubber-spring floating slab track*, Environmental Science and Pollution Research, 2021, vol. 28(11):13671–13689.
37. Major M., MindaI.: *Drgania i oddziaływania dynamiczne na budynki i budowle* [Vibrations and dynamic effects on buildings and structures], Zeszyty Naukowe Politechniki Częstochowskiej, Budownictwo, 2016, vol. 22 (172), pp. 223–327.
38. Faure B. et.al.: *Vibration mitigation by innovative low stiffness rail fastening systems for ballasted track*, Notes on Numerical Fluid Mechanics & Multidisciplinary Design, 2015 vol. 126, pp. 627–634.
39. Polak K.: *High-Speed Rail versus environmental protection. In High-Speed Rail in Poland: Advances and Perspectives*, [in. Żurkowski A., Ed., CRC Press], Warsaw, 2018, pp. 421–439.
40. Adamczyk J., Szałyga-Osypanka D.: *Systemowe rozwiązania ograniczenia oddziaływań dynamicznych na podtorze pojazdów kolejowych o prędkościach powyżej 250 km/h* [System solutions for limiting dynamic impacts on the trackbed of railway vehicles with speeds above 250 km/h], TTS Technika Transportu Szynowego, 2008, No. 5–6, pp. 80–84.
41. Ouakka S. et. al.: *Efficient mitigation of railway induced vibrations using seismic metamaterials*, Engineering Structures, 2023, vol. 284, 115767.
42. Lyratzakis A. et. al.: *Efficient mitigation of high-speed trains induced vibrations of railway embankments using expanded polystyrene blocks*, Transportation Geotechnics, 2020, vol. 22,100312.
43. Ouakka S., Verlinden O., Kouroussis G.: *Railway ground vibration and mitigation measures: Benchmarking of best practices*, Railway Engineering Science, 2020, No. 30(1), pp. 1–22.
44. Nielsen J. et. al.: *Reducing train-induced ground-borne vibration by vehicle design and maintenance*, International Journal of Rail Transportation, 2015, vol. 3 (1), pp. 17–39.
45. Coulier P. et. al.: *Subgrade stiffening next to the track as a wave impeding barrier for railway induced vibrations*, Soil Dynamics and Earthquake Engineering, 2013, vol. 48: 119–131.
46. Connolly D.P. et. al.: *Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils*, Soil Dynamics and Earthquake Engineering, 2014, vol. 66, pp. 78–88.
47. Garinei A., Risitano G., Scappaticci L.: *Experimental evaluation of the efficiency of trenches for the mitigation of train-induced vibrations*, Transportation Research Part D: Transport and Environment, 2014, vol. 32(0), pp. 303–315.
48. Kouroussis G. et. al.: *The effect of railway local irregularities on ground vibration*, Transportation Research Part D: Transport and Environment, 2015, vol. 39. pp. 17–30.
49. Guo W. et.all.: *A combination strategy of hollow-closed-wall in-filled trench and elastic bearing for reducing environmental vibration induced by high-speed train*, Soil Dynamics and Earthquake Engineering, 2020, vol. 133, 106136.
50. Kraśkiewicz C., Oleksiewicz W., Zbiciak A.: *Podkładki podpodkładowe w podsypkowej konstrukcji nawierzchni dróg szynowych – techniczne i formalne aspekty stosowania* [Under sleeper pads in ballasted rail track system – technical and formal aspects of use], Archiwum Instytutu Inżynierii Lądowej, 2017, No. 25, pp. 221–243.