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DOI: 10.35117/A_ENG_19_08_01

Practical aspects of applying the principles of environmental protection against vibrations in the process of preparation and implementation of railway investment

Abstract: Both in the case of reconstruction (modernization) of existing railway lines and construction of new ones - it is necessary to take into account the impact of these investments on the environment. One of such influences are vibrations caused by train passing. Vibrations transmitted to the building through the ground have an impact on: the construction of the buildings, the people staying in them and the vibration-sensitive devices if they are in the building. These receipts are not always sufficiently included in environmental documents. This issue often raises a number of doubts. The paper presents the basis for the assessment of the vibration effects mentioned above. Then the following is presented: an algorithm to take into account these influences at the stage of preparation and design and implementation of railway investments, the problem of determining the extent of zones of dynamic impact from the operation of the railway line, indications regarding the typing of representative buildings, rules for performing pre-realization tests of the impact of vibrations on representative buildings and on people in these buildings (dynamic background measurements) and the principles of post-implementation measurements, the problem of forecasting the impact of vibrations on representative buildings and on people in these buildings. It also presents some remarks about problems of protection of neighboring buildings against vibrations from construction works related to the implementation of investments.

Keywords: Environmental Protection; Vibrations, Railway investments

Introduction

Both in the case of reconstruction of existing railway infrastructure and construction of new railway lines, it is now required to take into account the environmental impact of these investments. One of the impacts that, along with noise, accompany the operation of railway lines are oscillations (vibration) caused by train journeys. These vibrations coming through the ground to buildings have an impact on the construction of buildings, people staying in buildings and on devices sensitive to vibrations if they are in the building (e.g. servers in railway control rooms) - Fig. **1**.

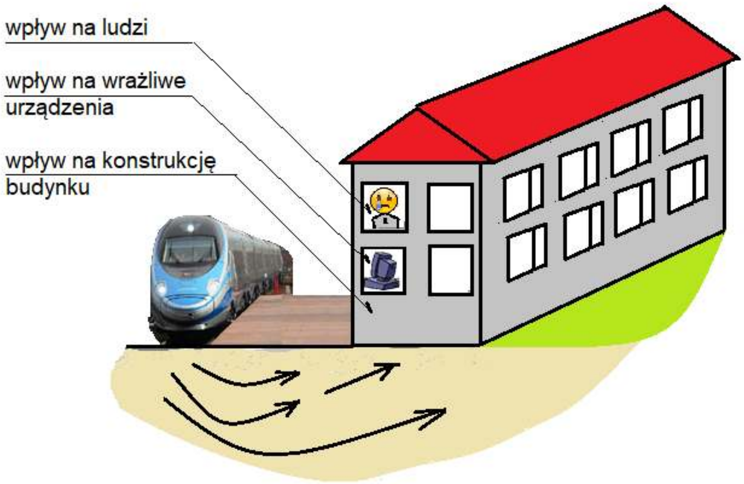

Fig. **1**. An ideogram of the impact of railway vibrations on the environment

These impacts are not always sufficiently clearly described in environmental documents (EIA, environmental decision). Despite the significant progress which, as a result of the activity of the PKP PLK Environmental Protection Office, has been achieved in the awareness of the railway services responsible for the preparation and supervision of investments (and perhaps due to this awareness), questions arise from both designers and contractors: how to consider the impact of vibrations on neighboring buildings? What principles should be followed?

This article is an attempt to answer some of these doubts. More detailed considerations and examples of applications can be found in the work [1].

Standards being the basis for assessing the impact of vibrations on the environment

The rules for measuring vibration and assessing their impact on neighboring buildings are contained in two Polish standards (constituting an amendment to PN-B-02170: 1985 and PN-B-02171: 1988):

- PN-B-02170:2016. Assessment of the harmfulness of vibrations transmitted through the ground to buildings.[2]
- PN-B-02171:2017. Assessment of the impact of vibrations on people in buildings. [3]

These standards are referred to, among others the provisions contained in the Regulation of the Minister of Infrastructure and Construction of November 14, 2017, amending the regulation on the technical conditions to be met by buildings and their location (Journal of Laws item 2285):

§ 325. *1. Residential buildings, collective housing buildings, and public buildings should be located in places least exposed to noise and vibrations, and if they occur and their levels will cause in these buildings the exceeding of the permissible noise and vibration levels specified in Polish Standards regarding permissible level values indoor sound, and assessment of the effects of vibration on buildings and people in buildings, effective protection should be used.*

2. (…)

§ 326. *1. The level of noise and vibrations penetrating the rooms in residential buildings, collective housing buildings and public buildings, excluding buildings for which it is necessary to meet specific requirements for noise protection, may not exceed the permissible* *values specified in Polish Standards for noise protection of rooms in buildings and assessment of the impact of vibrations on people in buildings, determined in accordance with Polish Standards regarding the method of measuring A sound level in rooms and assessment of the impact of vibrations on people in buildings.*

2. (…)

The above records clearly indicate that the assessment of the impact of vibrations on buildings and people in buildings should be made in accordance with Polish Standards regarding these issues, i.e. currently in accordance with PN-B-02170: 2016 and PN-B-02171: 2017.

Occasional attempts to apply German standards (e.g. DIN 4150. Erschütterungen im Bauwesen) or ISO standards have no justification in Polish legal regulations.

The procedure algorithm

The basic procedure algorithm is presented in Fig. **2**.

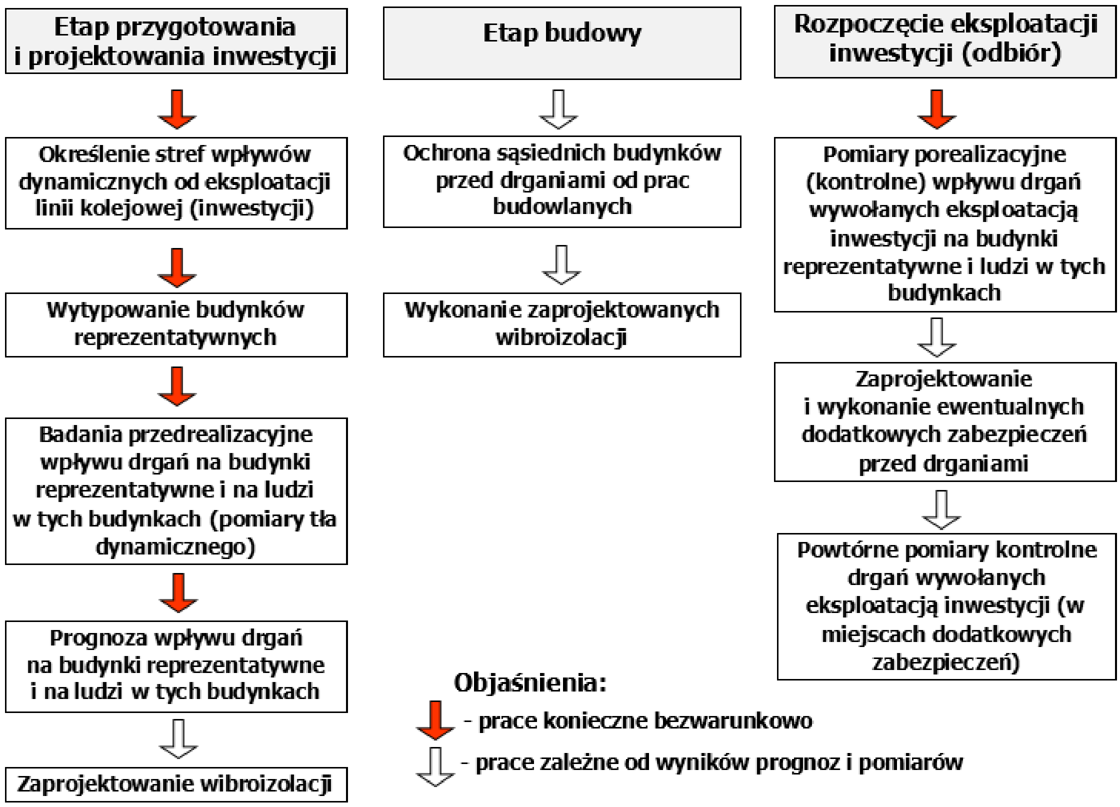

Fig. **2**. The basic algorithm to deal with environmental protection against vibration in the event of construction or reconstruction of a railway line

Determination of the range of dynamic impact zones from railway line operation

The range of dynamic impact zones caused by the operation of the future investment should be determined already at the stage of preparing environmental impact assessments for the railway investment. The determination of which buildings may be exposed to the excessive impact of railway vibrations on the structure of buildings and people staying in them depends on the expected range of these zones. This is the first step to determining the extent of further action.

Approximate values of the range of zones of railway vibration impacts referring to average ground conditions and buildings of a typical (correct) construction in good technical conditions are given below in Table **1**. The values of the range of the zones given in column 2 of the table determine the zones in which buildings may be damaged under the influence of railway vibrations. Since the zone ranges given in column 2 do not take into account the impact of vibrations on people in buildings, they can only be taken into account for buildings that do not have premises for permanent residence of people, such as outbuildings, garages, storage halls, etc. Because most protected buildings have rooms for permanent residence of people (housing, office buildings, etc.), the values of column 3 of Table **1** should be taken as the basic range of dynamic influence zones, i.e. 65 m for passenger traffic and 80 m for freight and mixed traffic (Fig. **3**). In exceptional cases of particularly unfavorable conditions, e.g. heavily irrigated land, these ranges may be greater, reaching for example for lines with freight traffic up to 120 m.

Tab. **1**. Approximate values of the range of railway vibration impact zones related to average ground conditions and buildings with a typical (correct) construction in the good technical condition [4]

Railway traffic generating vibrations	Range of the zone from the axis of the nearest railway track	
	Due to the impact of vibration on the building structure	Due to the impact of vibrations on people in the building
1	2	3
Passenger traffic	35 m	65 m
Freight and mixed traffic	45 m	80 m

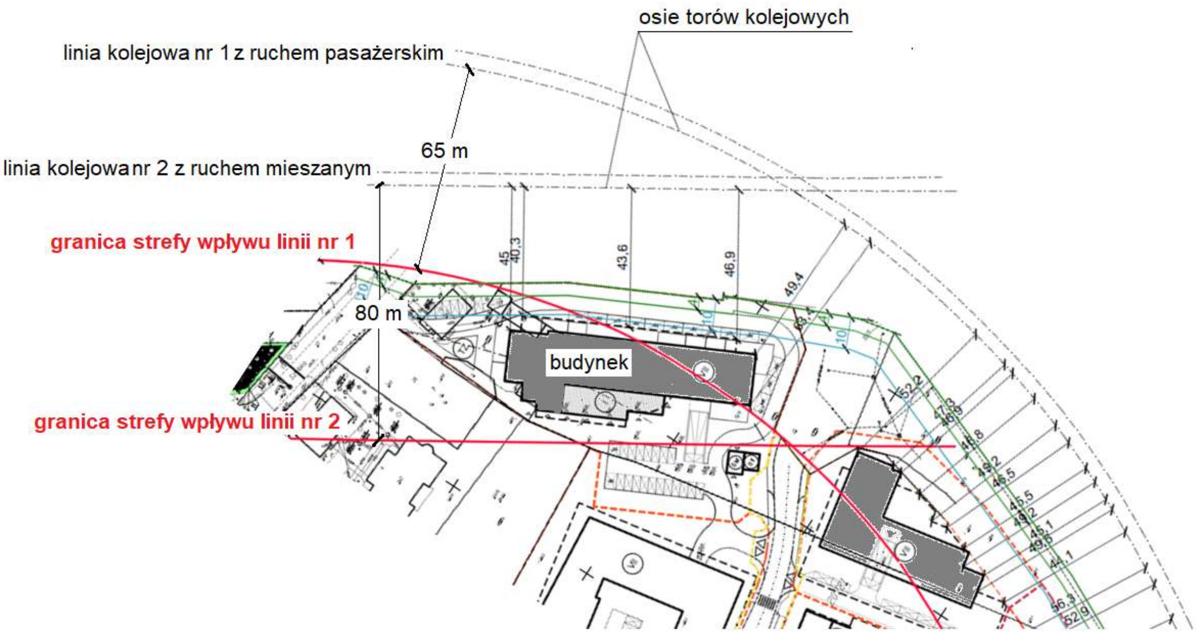

Fig. **3**. An example of determining the range of dynamic influence lines of railway lines in the case of a set of buildings (the marked building is subject to the effects of vibration generated by train journeys on two different railway lines)

Due to the fact that there are attempts to determine the zones of impact of vibrations on buildings on the basis of the criteria given in point 5.2 of PN-B-02170: 2016 entitled "Suppressing the impact of vibrations transmitted through the ground in the building calculations", it should be clearly stated that taking these criteria in the assessment of the impact of vibrations on existing buildings is incorrect.

The aforementioned point 5.2 of the cited standard contains a provision that in the design of buildings the impact of vibrations transmitted through the ground can be ignored if the amplitude of the accelerations of the horizontal components of the ground vibrations at the building foundation does not exceed the value of 0.05 m/s2. Guided by this criterion, it was assumed that in the case of average geotechnical conditions occurring through propagation from the source of vibrations to the building and flat terrain, the design calculations of the building may omit the impact of vibrations transmitted through the ground to the building, if the designed building is located at a distance greater than 25 m from the axis of the railway track. There is a statement at the end of this point: "The above conditions for omitting the effect of vibrations transmitted through the ground to the building structure may not be used in diagnostic studies." From the content of point 5.2 of the standard, it is clear that the criteria given apply only to designed buildings and cannot be used to assess the impact of vibrations on existing buildings. Moreover, these criteria also do not take into account the issue of the impact of vibrations on people in buildings, so they are not useful for determining the extent of zones of the impact of railway vibrations on existing neighboring buildings.

Typing representative buildings

When selecting representative buildings, there should be taken into account:

- location of buildings with the sources of vibration (distance from tracks, longitudinal or transverse orientation of the building to the track),
- types of building structures, their technical condition and dynamic features,
- their representativeness for entire groups of neighboring objects,
- conditions of vibration propagation,
- the shape of the cross-section of the railway road (on the embankment and the cross-section) and types of a railway pavement structure,
- availability of construction documentation or the possibility of inventory taking,
- archival measuring materials,
- access to buildings and individual rooms for measurements.

Pre-implementation studies of the impact of vibrations on representative buildings and people in these buildings (dynamic background measurements) and post-implementation measurements

Both pre-implementation and post-implementation studies include measurements of railway vibrations in representative buildings and assessment of the impact of these vibrations on these buildings and on people staying in them. The tests should be carried out under the requirements specified in the PN-B-02170: 2016 and PN-B-02171: 2017 standards. The registration applies to vibrations with frequencies from 0.5 to 100 Hz. The range of vibration measurements in each building should include (Fig. **4**):

- Measurement of kinematic excitation - a measurement of three vibration components (x, y, and z) in a rigid node of the structure located on the side of the vibration source on the building foundation (point 1 in fig. **4**) or on the basement wall at ground level (point 2 in Fig. **4**).

- Measurement of vibrations affecting people - measurement of three components of the floor vibrations (x, y and z) in the center of the ceiling of a large room (in accordance with PN-B-02171: 2017, use a measuring disk - Fig. **5**) on the ground floor and on the top floor for permanent residence people (points marked with L in figure 4); in the case of tall buildings, it may also be necessary to measure vibration and assess their impact on people on one or two intermediate floors.

Pre-implementation studies (dynamic background measurements) have a dual purpose:

- They provide information on the current dynamic impacts on building structures and on people staying in them for the purpose of later comparison of these influences with the results of post-implementation studies.
- They provide data on the response of individual buildings to kinematic excitation, which allows verification of numerical models for forecasting the impact of vibrations on buildings and people in buildings after the implementation of the investment, and then, if necessary, proper designing of vibration isolation in the track using simulation calculations.

To ensure that the results of pre- and post-implementation tests can be compared, vibration measurements before and after the investment should be carried out at the same measuring points. Therefore, among others during both tests, the location of the measuring points should be clearly defined, along with a sketch to identify these points. After each test (measurements of vibrations in a given building), a test report should be prepared, the scope of which has been specified in PN-B-02170: 2016 and PN-B-02171: 2017.

Considering the second of the above-mentioned objectives, the registration of vibrations at all measuring points in the tested building (as well as all the components of vibrations at these points) must be carried out simultaneously.

Post-implementation tests are aimed at determining whether the requirements for the protection of buildings and people in buildings against vibrations have been met and whether any additional measures are necessary to ensure that these requirements are met.

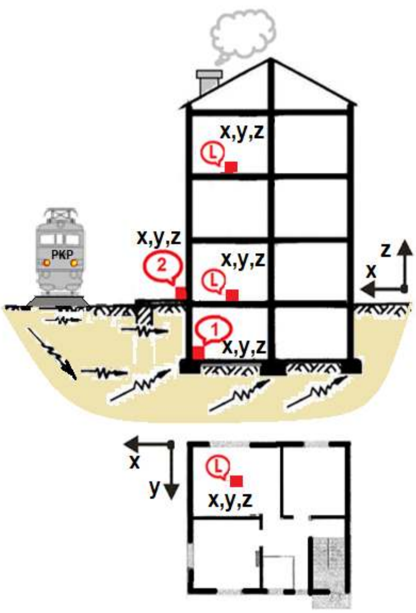

Fig. **4**. A diagram of measuring points distribution (x, y, z - components of measured vibrations)

Fig. **5**. An example of a measuring disk for measuring the impact of vibrations on people

It should be emphasized that Art. 147a of the Act "Environmental Protection Law" of 2001 requires that emission measurements (in this case it concerns vibration emissions) by an accredited laboratory within the meaning of the Act of 30 August 2002 on the conformity assessment system (Journal of Laws of 2004, No. 204, item 2087, as amended). That is, pre- and post-implementation measurements, as they are required as part of the assessment of the impact of vibrations on the environment, should be performed by laboratories accredited to measure vibrations according to PN-B-02170: 2016 and PN-B-02171: 2017.

Forecast of impact of vibrations on representative buildings and people in these buildings

The forecast of the impact of vibrations caused by the operation of the railway line on each of the representative buildings should include:

1) Determining the expected time course of vibrations of the building foundations that will be used as kinematic forcing in the dynamic calculations of the building. This is one of the most important elements of the forecast. The basis for determining this forcing should be the results of vibration measurements obtained for a similar existing vibration source (from a measurement database) using a vibration propagation model, taking into account the function of the transition of vibrations from the ground to the building foundation. Note: railway vibrations are complex vibrations and it is not correct to numerically generate forcing e.g. in the form of a sine wave.
2) Preparation of a building construction model (FEM spatial model is recommended) for dynamic calculations.
3) Assessment of forecast dynamic impacts on the building:
   - using the SWD (Dynamic Impact Scale) scales given in PN-B-02170: 2016 if the building qualifies for such assessment,
   - if the building is not subject to assessment by SWD scales, then dynamic calculations should be performed on the building model to calculate dynamic forces (inertia forces) additionally loading the structure and checking the effort of the structural elements.
4) Assessment of forecasted effects of vibrations on people on individual floors of the building intended for permanent residence of people. For this purpose, dynamic calculations should be made on the building model and as a result of these calculations, the most adverse effective values (RMS) of acceleration (or speed) of vibrations in one third octave frequency bands in accordance with PN-B-02171.

In the summary of the forecast, it should be indicated in which buildings the criteria for vibration protection are met, and for which buildings it will be necessary to apply technical measures limiting the impact of vibrations, e.g. in the form of the use of vibration isolation in the construction of a railroad (pavement).

Designing vibration isolation

Reducing the impact of vibration on neighboring buildings can be achieved, among others by introducing vibration insulation into the railway structure (Fig. **6**).

The basic algorithm for designing vibration isolation in the construction of a railway road is shown in Fig. **7**.

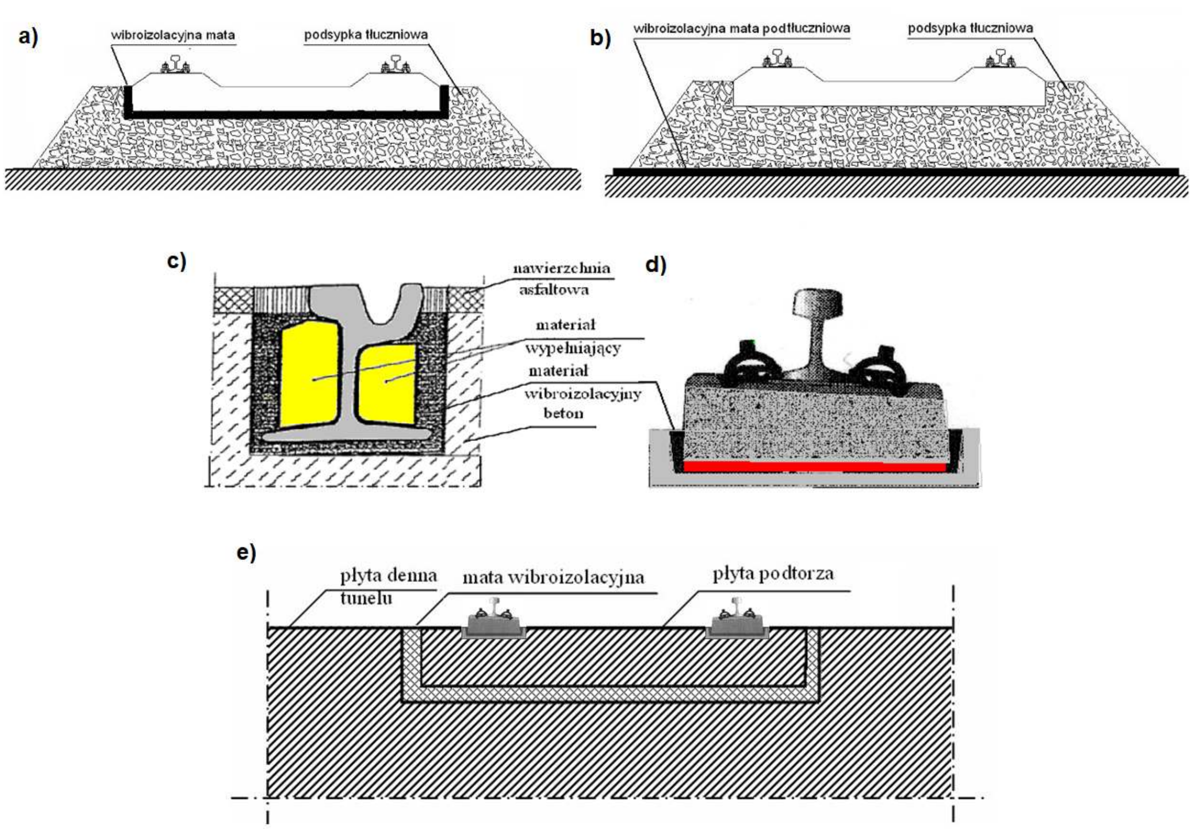

Fig. **6**. Examples of anti-vibration solutions in railroad construction: a - sub-sleeper mat, b - sub-ballast mat, c - ERS system (buffer rail),d - EBS system (block in the buffer zone), e - a mat under the track panel

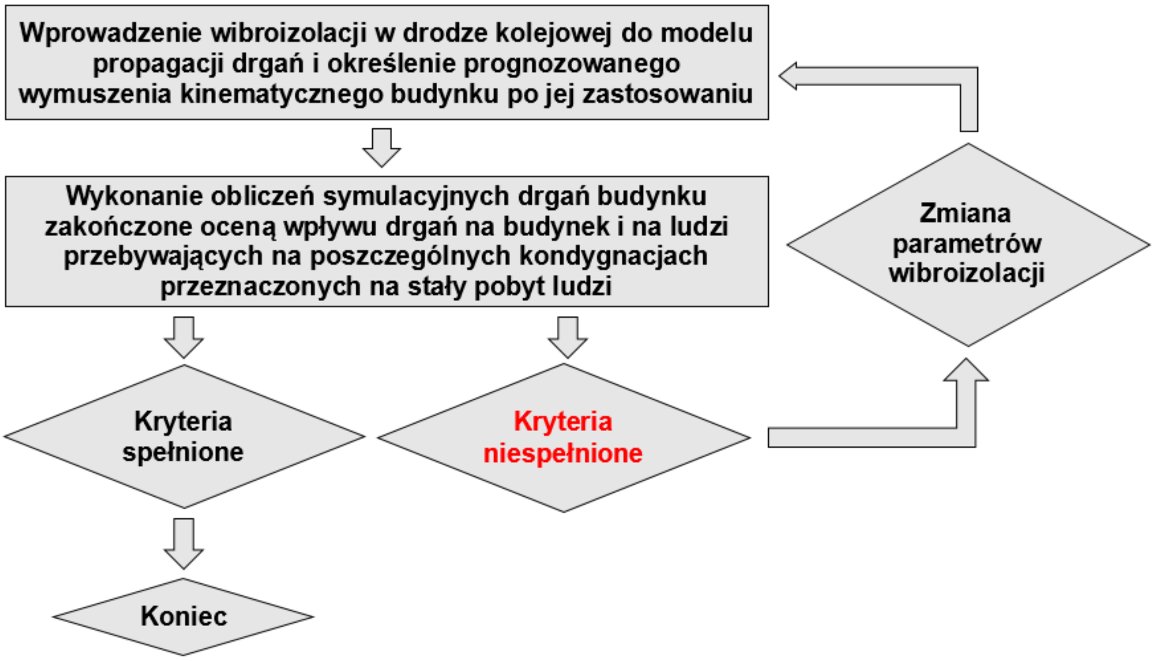

Fig. **7**. An algorithm for designing vibration isolation in the construction of a railway road using the simulation calculation technique

The goal is to design vibration insulation so that the effects of vibration on the building and people in the building forecast after its application meet the following criteria (see standards PN-B-02170: 2016 and PN-B-02171: 2017):

- WODB<1 indicator,
- WODL<1 indicator.

Where:

- WODB - buildings' vibration perception index - the largest among the values of the ratio of maximum velocity/acceleration values determined in individual 1/3-octave bands determined by analyzing the vibrogram in 1/3-octave bands to the velocity value or acceleration corresponding to the lower limit of taking dynamic effects on buildings into account covered by SWD scales in the same frequency band; WODB is expressed by two numbers: dimensionless, determined as above, and the value of the central frequency of the band in which this ratio was determined (Fig. **8**).
- WODL- human vibration perception index - the largest among the values determined in individual 1/3-octave bands expressing the ratio of the values of effective velocity/acceleration values of vibrations determined as a result of the analysis of the vibrogram in 1/3-octave bands to the effective velocity/acceleration values corresponding to the threshold of vibrations by a human in the same frequency band; WODL is expressed by two numbers: dimensionless, determined as above, and the value of the central frequency of the band in which this ratio was determined (Fig. **9**).

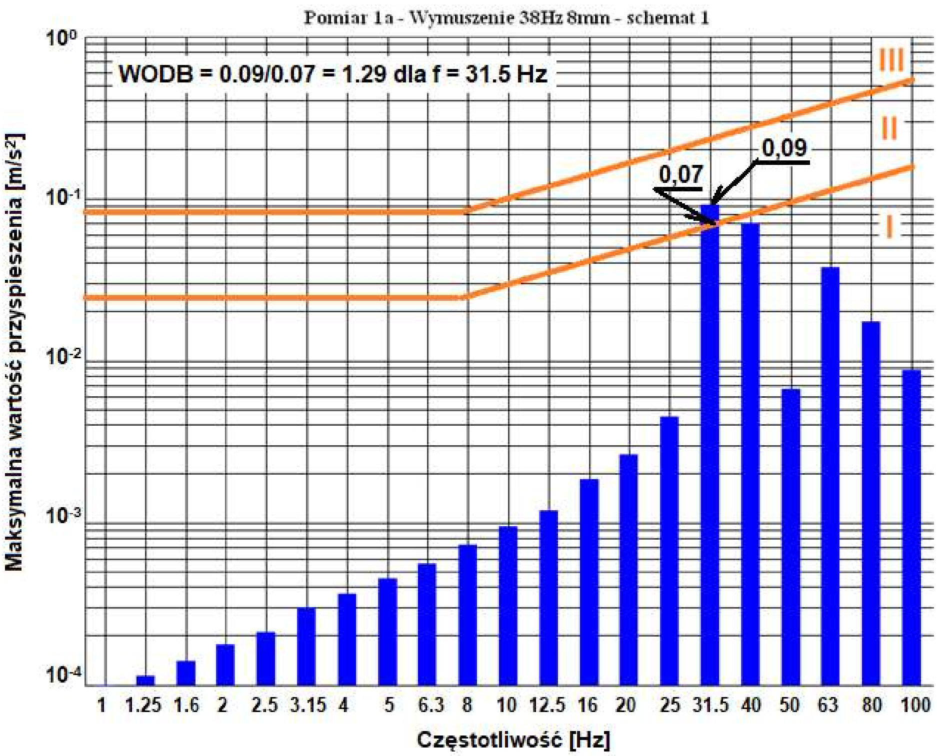

Fig. **8**. Method of determining the WODB indicator

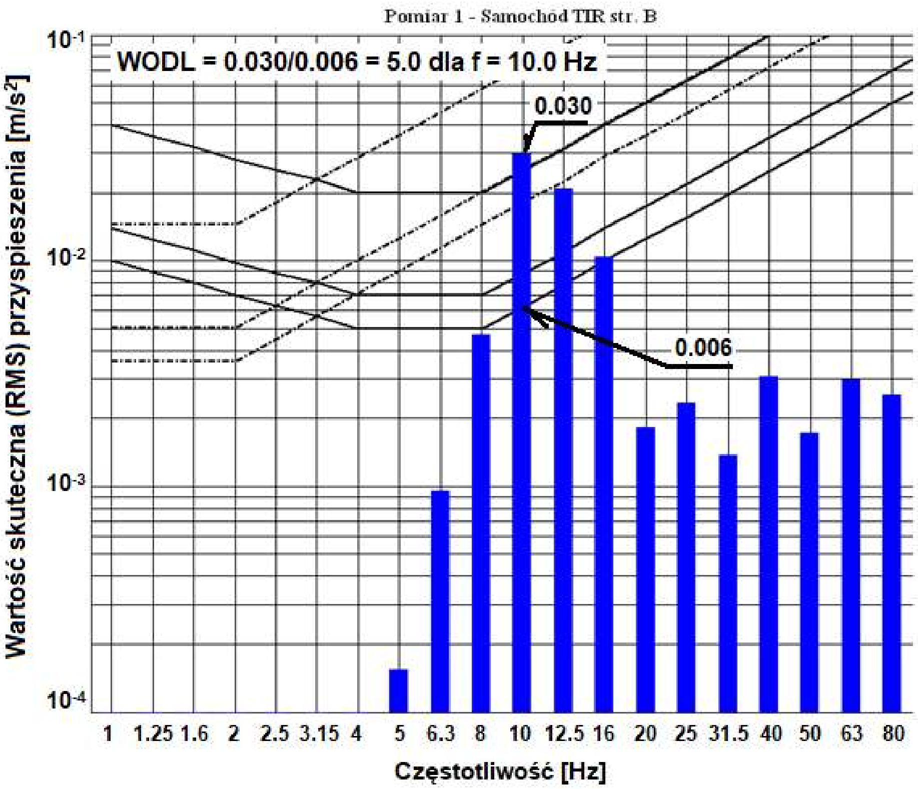

Fig. **9**. A method of determining the WODL indicator

It is worth noting that in the case of buildings intended for permanent residence of people, it is usually determined by the fulfillment of the second of the criteria, i.e. the fulfillment of the condition regarding the impact of vibrations on people (WODL<1) [1].

Protection of neighboring buildings against vibrations from construction works related to the implementation of the investment

Assumption: in the case of construction vibrations, the impact on people is ignored, and attempts to prevent damage to buildings near the area of construction works. The condition is that work causing noise and vibration is not carried out at night, i.e. from 10 PM to 6 AM.

The following tasks should be successively done:

- analysis of design and environmental documentation - determining what technologies will cause vibrations, what requirements are included in the EIA or ROŚ, situational plan,
- initial risk assessment ("a priori" opinion) and determining the scope of further necessary actions analyzing the design and environmental documentation - determining what technologies will cause vibrations, what requirements are in the EIA or ROS, situational plan,
- determining the extent of impact zones for individual works,
- professional damage inventory with photographic documentation (before work commences),
- control measurements of vibrations and assessment of their impact on neighboring buildings,
- determination of safe distances to perform these works and permissible operating parameters of devices causing vibration,
- periodic (less often continuous) monitoring of the impact of vibrations during construction.

Among the sources of construction vibrations can be mentioned:

- driving foundation piles into the ground or deepening sheet piles by impact (slow-fall hammer) or vibration (vibrating head, vibratory hammer),
- drilling piles in soil (especially rocky) and, above all, vibrating reinforcement for these piles,
- compaction of the substrate with various types of vibrating equipment, including soil, foundation layers and surface layers with the use of road vibrating rollers,
- work of heavy equipment at the construction site, e.g. excavators,
- passage of heavy-duty construction cars,
- demolition works.

In the case of railway tunnels, there is a problem of vibrations caused by tunneling. The basis for assessment is the building vibration measurement made following the principles set out in point 6 of this paper and the requirements given in the PN-B-02170: 2016 standard. The assessment of forecast dynamic impacts on a building consists of performing dynamic calculations on a building model to calculate dynamic forces (inertia forces) additionally loading the structure and checking the effort of the structural elements. If the building qualifies for the assessment using the SWD (Dynamic Impact Scale) scales given in PN-B-02170: 2016, then the assessment can be made using these scales.

Conclusions

The application of the above principles should result in harmonizing the approach to the subject of the impact of vibrations on the environment, both in the environmental documentation and at the subsequent stages of preparation and implementation of railway investments. It is particularly important to include them in the tender documentation to clearly define the requirements for the future contractor of the investment.

One should be aware that work in the field of vibration measurements, simulation calculations and forecasting the impact of vibrations on buildings and people in buildings, as well as designing vibration isolation are highly specialized. Therefore, their contractor should be required to have experience in this area and appropriate permits (accreditation to perform measurements following PN-B-02170: 2016 and PN-B-02171: 2017, certificates of measurement sensors, building permits).

Source materials

[1] Kawecki J., Stypuła K.: *Zapewnienie komfortu wibracyjnego ludziom w budynkach narażonych na oddziaływania komunikacyjne.* Wydawnictwo PK, Kraków 2013

[2] PN-B-02170:2016. Ocena szkodliwości drgań przekazywanych przez podłoże na budynki.

[3] PN-B-02171:2017. Ocena wpływu drgań na ludzi w budynkach.

[4] *Wytyczne do projektowania rozwiązań minimalizujących drgania od linii kolejowych*. Opracowanie wykonane pod kierunkiem K. Stypuły w Instytucie Mechaniki Budowli Politechniki Krakowskiej na zlecenie PKP Polskie Linie Kolejowe S.A. Kraków, grudzień 2015.