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DOI: 10.35117/A_ENG_16_04_02

Metro in Warsaw as an example of protection against vibration in the process of rail transport infrastructure creation

Abstract: The work addresses the problem of environmental protection against vibration caused by rail transport considered in the stage of preparation and design of rail transport infrastructure. In the example the subway in Warsaw, guidelines and standards for assessing the impact of vibration on buildings and people in these buildings were indicated. We presented procedures for protection against vibrations in the case of the rail transport and discussed kinds of analyses of the impact of vibration on structures of buildings and people staying in them. We also described the design procedure of vibroisolation in the structure of the rail track.

Keywords: transportation vibrations; rail vibrations; vibroisolation; subway; building vibrations

Introduction

Under the new perspective of EU funds, a number of investments in the reconstruction and development (modernization) of railway transport infrastructure are planned in our country. This will apply especially to the railway infrastructure (reconstruction and expansion of railway stations and railway lines, the establishment of high-speed trains), but investments of urban rail transport (tram, subway) will be also included.

The inclusion of the requirements of environmental protection is one of the conditions for the settlement of investment and reimbursement of EU funds. One of these requirements applies to reduction of the impact of vibrations generated by rail transport on buildings and people in these buildings. The issue considering the impact in the investment process is presented below in the example of the Warsaw subway. A wider range of issues on this subject can be found in other publications of the authors. [1-4].

Guidelines and standards regarding the impact of vibration on buildings and people in the buildings

For more than a quarter of a century, underground facilities in Warsaw were designed and built on the basis of the railway regulations, and documentation swarmed with derogations from these provisions. Currently, underground facilities must comply with the conditions set out in the Regulation of the Minister of Infrastructure of 17 June 2011 on the technical conditions that should be met by buildings and their location.

Annex 2 to this regulation entitled REQUIREMENTS FOR LIMITATIONS OF IMPACT VIBRATION regulates the issue of protection against vibration of subway. This

annex contains the following provisions:

1. Technical solutions, including the construction of the tunnel and the track surface should provide protection against the influence of the dynamic vibration on surrounding buildings, taking into account the requirements of the Polish Standard PN-B-02170: 1985 and PN-B-02171: 1988. It should be included the following parameters for assessing the correctness of solutions for vibration damping:

1) the impact of vibration on the structure of building - the maximum rate of vibration perceptibility - 0.70,

2) the impact of vibrations on people - the maximum rate of vibration perceptibility - 0.95, where the rate of vibration perceptibility is the ratio of the actual value of the vibration to the limit values for specific frequencies.

2. The range of operating area of dynamic interactions of underground sections of the subway line with the surrounding buildings, in average ground conditions, in flat area is determined on 40 m from the extreme wall of the nearest tunnel or subway station, on both sides of the underground line.

3. The range of operating area of dynamic interactions of above-ground sections of the subway line with the adjacent buildings is dependent on the local conditions and should be determined in each case on the basis of specific analysis taking into account the results of vibration measurements.

4. The basic way of protection of neighbouring buildings against vibrations caused by the operation of subway is to design vibration isolation in the construction of track surface. The project should include a forecast of the impact of the vibration on the neighbouring buildings after applying vibration isolation.

5. The places of immediate vicinity - adhesion of buildings to the construction of underground buildings - should be provided with vibration insolation protecting the buildings against propagation of excessive vibrations.

6. Vibroisolation protection should be designed so that the level of the assumed impact of vibrations on people residing in the buildings does not exceed the threshold of perceptibility of vibrations by people.

7. Subway line should be equipped with at least two points of vibration measurement, ensuring the monitoring in a continuous way, the level of vibration at the substructure and buildings adjacent to the subway line.

8. In the case of need to carried out works causing vibrations significant for building facilities it should be:

1) determine the scope of the impact of these vibrations;

2) perform a forecast of their impact on those objects;

3) make an assessment of the impact on the basis of control measurements during the execution of works.

As it was mentioned in the above-mentioned Regulation, the principles of diagnosis and assessment criteria for the impact of vibrations on the structure of buildings and people staying in them are contained in two Polish standards that were developed at the Institute of Structural Mechanics Cracow University of Technology:

- PN-B-02170:1985. Evaluation of the harmfulness of vibrations transmitted by the ground on buildings.

- PN-B-02171:1988. Evaluation of the impact of vibrations on people in buildings.

The evaluation criteria included in these regulations are the basis for the correct design of buildings and protection of people residing therein from excessive vibrations.

Procedures for protection against vibration investments in rail transport

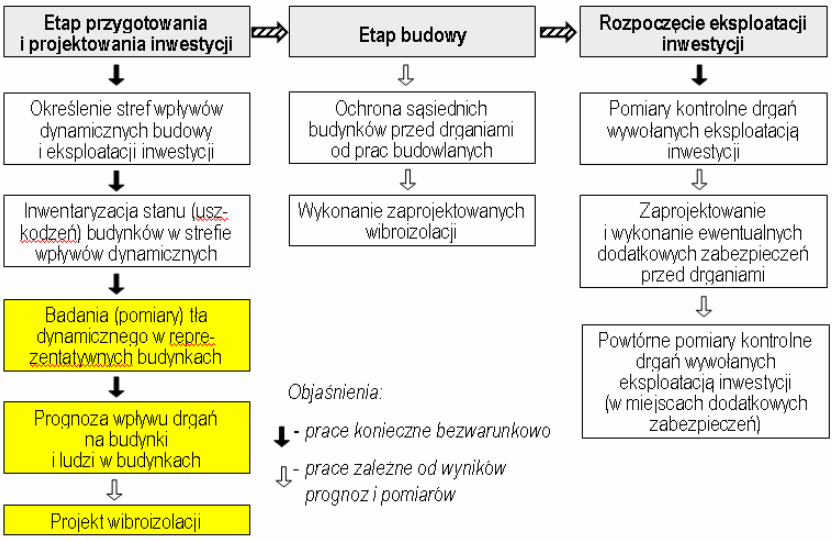
Actions to protect buildings and people in these buildings against vibrations should be carried out in the correct order. They can be divided into three main stages:

- Preparation stage of the investment - including the preparation of an assessment or report about the impact of the project on environment and development of the investment; in this stage it is performed an inventory of damages in the buildings located in the impact zone of the investment, and considering vibrations, it should be performed successive measurements of dynamic background, the forecast impact of vibrations on buildings and people in these buildings, design of protective features such as vibroisolations or systems for vibration monitoring.

- Execution stage of the investment (construction) - covering the protection of buildings against construction vibrations and completion of vibroisolations,

- Stage of starting exploitation of the realized investment - including control measurements of vibrations influencing buildings and people in the buildings, possible design and implementation of additional vibroisolation protection and re-check measurements to confirm the effectiveness of the protection.

An example algorithm of the described procedure is shown in Fig. 1.



1. Example of a work schedule for the protection against vibrations in the case of rail transport investment (works directly related to simulation calculations and design of vibroisolation are highlighted in yellow).

This algorithm can be subjected to some modifications related to local requirements and conditions under which the investment is carried out (e.g. the requirement for monitoring vibrations in the case of subway), or the organization of the investment process, e.g. in the case of investments "design and build", in which part of the work related to the preparation of the investment is on the side of the investor, whereas a further part of the design is carried out by the project contractor.

The latter situation can be traced on the example of the construction of the subway line in Warsaw. The Warsaw Subway commissions the analysis of impact of vibration and dynamic loads on structures of buildings and people staying in them, in the framework of investment preparation, e.g. inventory of the buildings in the subway impact area and the construction project before tendering on the execution of subsequent stages of the second subway line in the system "design and build". Further works are already contracted by a company found in the tender for the implementation of the particular underground section. And so in the case of the central section of the second subway line there were the following works:

- Design of vibroisolation,
- Design of vibration and noise monitoring during construction,
- Design of vibration and noise monitoring during exploitation phase,
- Design of measurements of vibrations caused by the movement of subway trains in the final stage,
- Measurements of monitoring vibration and noise during construction,
- Execution of the system monitoring vibration generated by subway,
- Development of a report on the ex-post vibration measurements at riding trains in the second subway line in Warsaw.

In the case of reconstruction of railway structure without altering its structure, measuring before the final realization in different buildings and delimitation of their influence on the building and people in the building can be sufficient to determine if and where it is necessary to use an additional vibration isolation. The simulation calculations aimed to design effective vibration isolation are limited only to the buildings in the vicinity, where the vibration isolation is needed.

Analysis of the impact of vibration on structures of buildings and people staying in them

Below are presented rules for the implementation of such analysis in the example of development made by the authors for the central section of the second subway line in Warsaw.

The whole elaboration included:

- review of the construction of buildings for selected objects that are representative for detailed analysis (simulation measurements and calculations),
- development of structural models of selected buildings with regard to their technical condition and performance of photographic documentation of structural elements requiring reinforcement (building cards) - see Fig. 2,
- tests (measurements) of dynamic influences (dynamic background) of terrestrial communication in streets which are located in the zones under the influence of subway vibration (40 m from the walls of tunnels and stations),
- verification of structural models of individual buildings - see Fig. 3,
- analysis of dynamic influences caused by buses and heavy wheel stock on buildings and people staying in them,

- analysis of the dynamic influences caused by trams on buildings and people stayed in them,
- forecast dynamic influences of operating underground on buildings and people stayed in them,
- forecast dynamic influences coming from subway, trams and wheel traffic on buildings and people staying in them,
- synthesis of forecasting the impact of subway vibration on the construction of buildings and people staying in them.

On the considered impact area of subway, 473 buildings were inventoried.

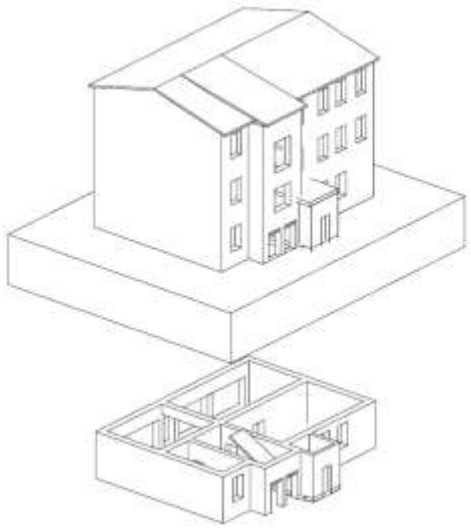
In order to carry out detailed research and analysis including measurement of dynamic background, modelling and performance of simulating calculations, representative buildings were selected. The following criteria were taken into account in the selection:

- features affecting the dynamic response of structures, and therefore the type of construction and materials from which it is made, dimensions - including the number of floors, the condition of the structure, etc.,
- qualification of the building for historic monuments,
- allocation of rooms (due to the assessment of the impact of vibration on humans),
- distance of the building from the underground tunnel, tram tracks and roads,
- access to the buildings and individual rooms (the consent of the owners).

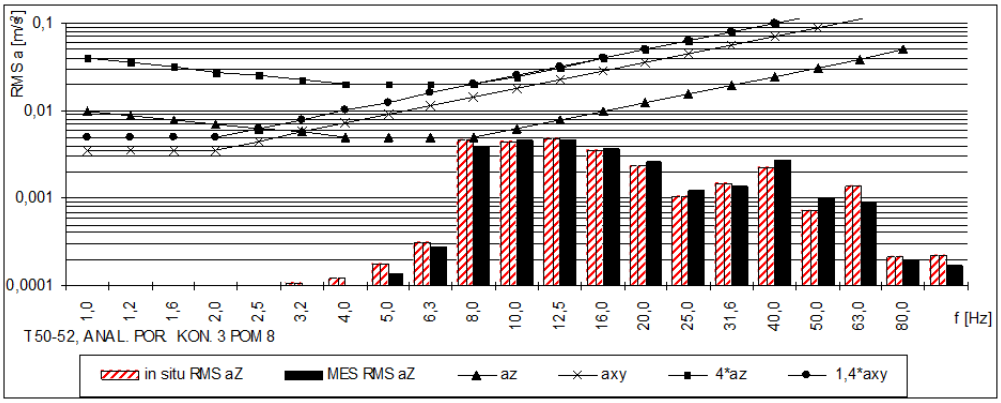
In terms of the dynamic characteristics the following types of buildings were distinguished:

- low to medium-high (up to 5 ground floor) buildings of traditional brick construction,
- medium-high and high (up to 16 ground floor) residential buildings (possibly with the ground floor for shopping and service destination) or the office buildings with framework, slab-girder or monolithic construction,
- unusual low and medium-tall buildings (sacral objects, post-industrial buildings, etc.),
- skyscrapers.

Given these criteria, 77 representative buildings located in the area under the consideration were selected for measurement and dynamic analysis.

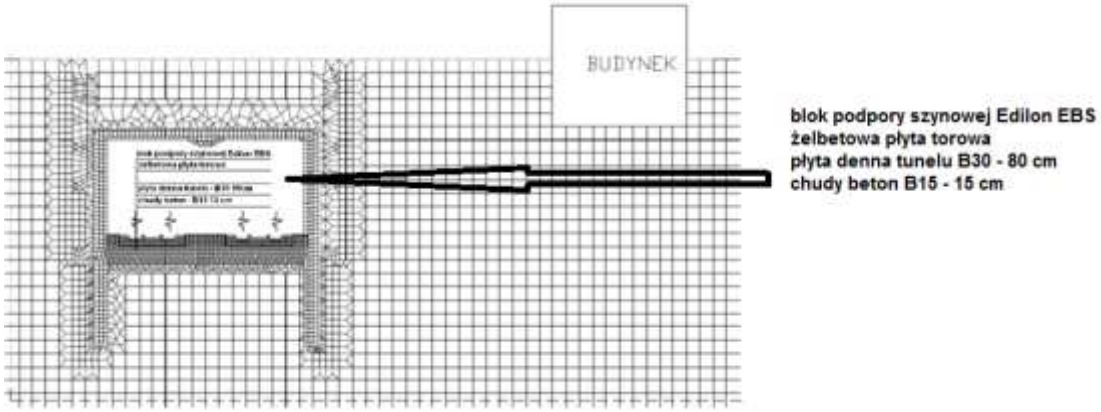


2. Visualization of computational model of the building (whole and single storey)

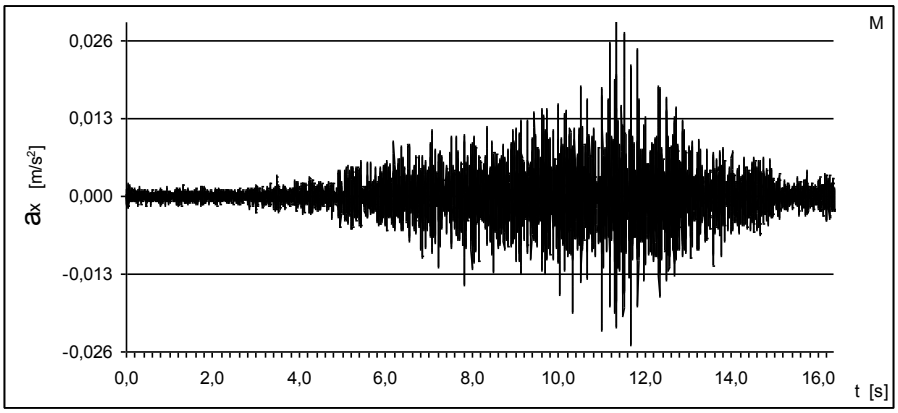


3. Verification of the model - a comparative analysis of the impact of vertical vibrations on humans in the third floor of one of the representative buildings in the case of passing track- according to in situ research and numerical simulation

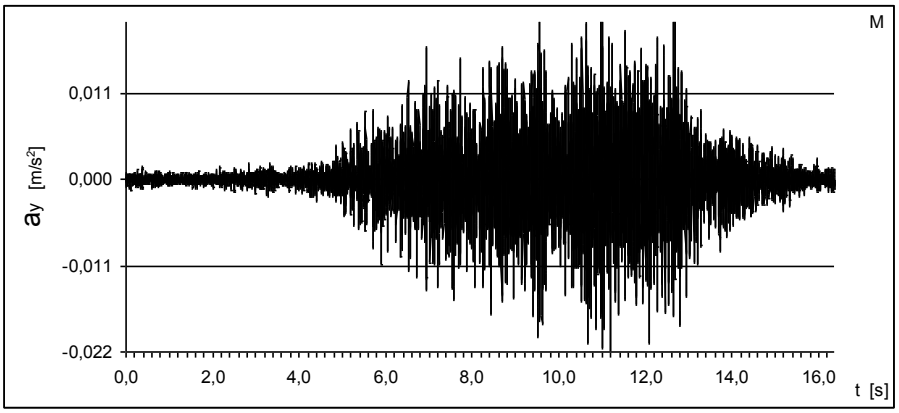
The basis of simulation calculations is to determine the projected kinematic force in the form of vibration waveform of the foundations of the considered building. For this purpose, a model of vibration propagation from the vibration source to the foundations of the building (Fig. 4) is constructed and the projected vibrograms of the foundation are determined (Fig. 5 - 7).



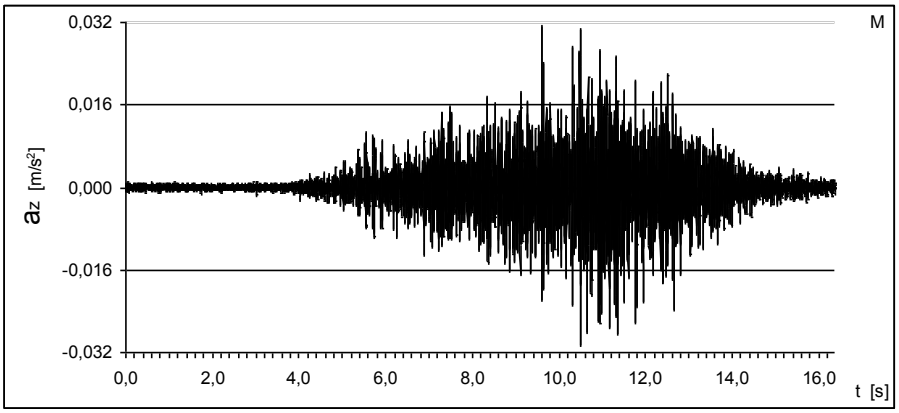
4. Example of the model of vibration propagation in the Bielany section of the first subway line in Warsaw



5. Component x (horizontal component parallel to the axis of the tunnel) of projected vibrations of building foundations generated by subway

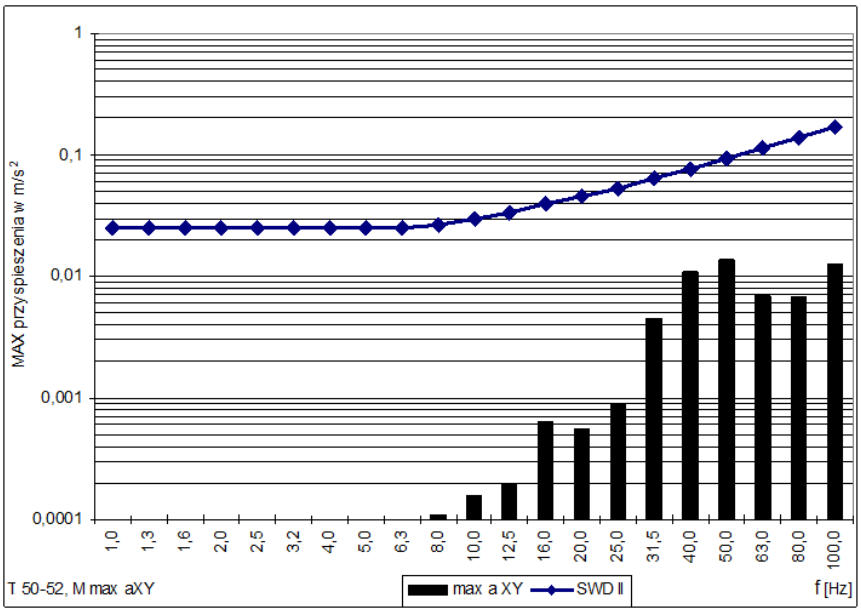


6. Component y (horizontal component perpendicular to the axis of the tunnel) of projected vibrations of building foundations generated by subway

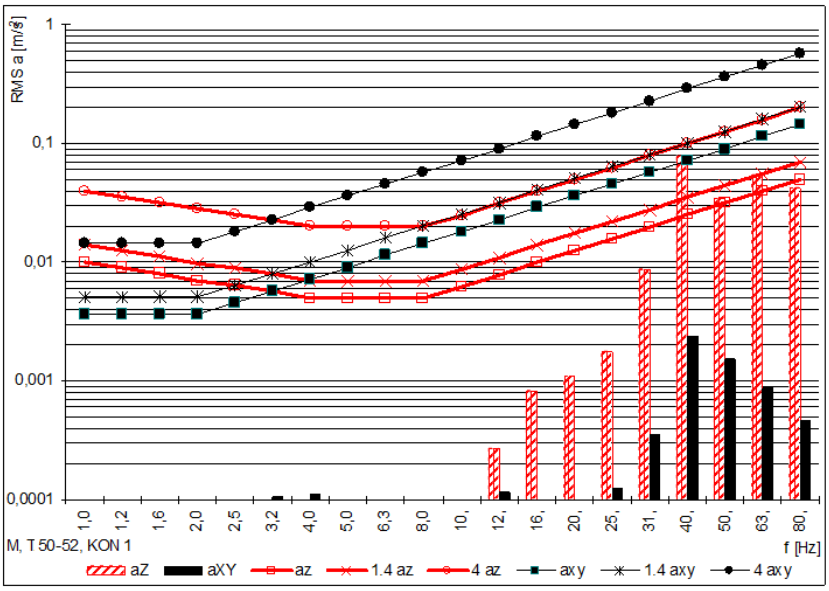


7. Component z (vertical component) of projected vibrations of building foundations generated by subway

The obtained for each building projected vibrograms of its foundations were used to perform dynamic calculations of the building and development forecasts of the vibration impact on the structure of the building (Fig. 8) and the people in the building (Fig. 9).



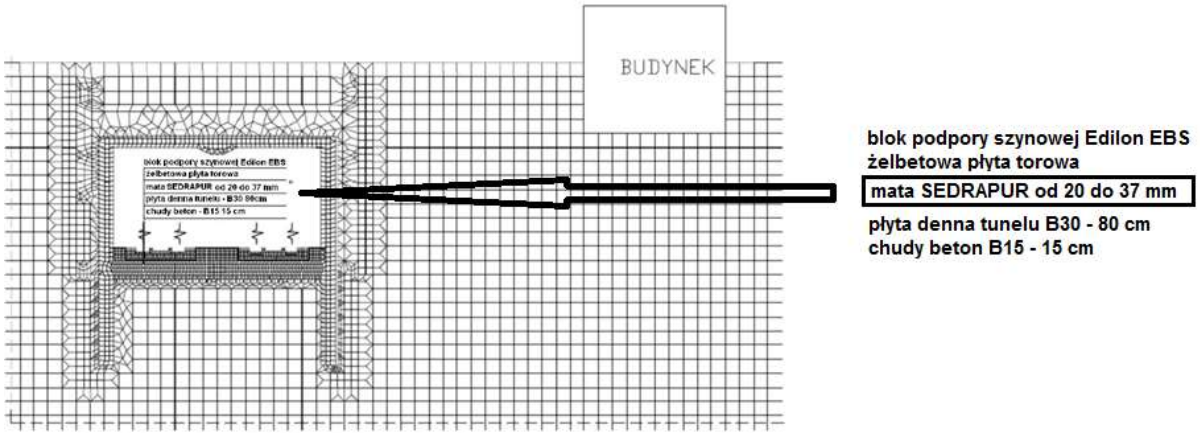
8. The projected impact of vibrations generated by the subway on the building structure - evaluation using the scale SWD-II



9. The projected impact of floor vibration on people in the first floor of the building during subway exploitation

The procedure for designing vibroisolation

Designing vibroisolation is the next stage, which consists in a selection of vibration isolating mats with appropriate parameters. To achieve that, the analysed vibroisolation is implemented into the model of vibration propagation in the railway structure (Fig. 10) and a new kinematic constraint in relation to the respective representative buildings is set. Using this constraint, dynamic calculations by checking the effect of vibrations on people on each floor is performed. If the results of this calculation do not meet the required criteria, the calculation should be repeated by changing the parameters of vibroisolation.



10. Propagation model to design vibroisolating mats in Bielany section of the first underground line in Warsaw

Summary

In the example of the subway investment in Warsaw, we presented the scope and methodology that take into account the effect of vibrations on surrounding buildings and people residing in the buildings.

The authors of this study have done a similar analysis also for two other sections of the second subway line, i.e. the western and eastern-northern section. In addition, to the central section of the second subway line in Warsaw, additional items were elaborated at the Institute of Structural Mechanics Cracow University of Technology:

- Project of vibration monitoring during the operational phase,
- Project and ex-post measurements of vibrations caused by subway trains,
- Monitoring system of vibrations caused by subway trains during the operational phase,
- Post-implementation measurements of vibrations caused by subway trains.

We also performed projects of vibration isolation in railway diametrical tunnel in Warsaw, railway stations Katowice Osobowa and Kraków Główny as well as the underground railway station Łódź Fabryczna and projects of vibroisolation in several tram lines in Warsaw (e.g. Śląsko-Dąbrowskim Bridge) and Kraków.

Source materials

[1] Kawecki J., Stypuła K.: Zapewnienie komfortu wibracyjnego ludziom w budynkach narażonych na oddziaływania komunikacyjne. Wydawnictwo PK, Kraków 2013
[2] Kozioł K., Stypuła K., Obliczenia symulacyjne w projektowaniu wibroizolacji nawierzchni szynowych. Wybrane przykłady zastosowań, DROGI Lądowe – Powietrzne – Wodne, Nr 10/2010 (29), str. 95 – 109
[3] Stypuła K.: Drgania generowane w podłożu przez transport szynowy i ich wpływ na budynki i ludzi w budynkach. Mat. XXIV Ogólnopolskiej Konferencji Warsztat Pracy Projektanta Konstrukcji „Naprawy i wzmocnienia konstrukcji budowlanych", Wisła 2009, t. II, str. 395-420
[4] Stypuła K.: Nowoczesne wibroizolacje. Builder, Nr 10, październik 2009, s. 66-70.
[5] PN-B-02170: 1985. Ocena szkodliwości drgań przekazywanych przez podłoże na budynki.
[6] PN-B-02171: 1988. Ocena wpływu drgań na ludzi w budynkach.