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# EXPERIMENTAL VERIFICATION OF THE DEVELOPED SOIL MODEL DESCRIBING THE PROPAGATION OF VIBRATION WAVE IN THE GROUND

**Jarosław Bednarz**

*AGH University of Science and Technology*
*Faculty of Mechanical Engineering and Robotics*
*Department of Robotics and Mechatronics*
*Mickiewicza Av. 30, 30-059 Krakow, Poland*
*tel.: +48 12 617-35-11, fax: +48 12 634-35-05*
*e-mail: bednarz@agh.edu.pl*

***Abstract***

*The problem of propagation of vibration waves in soil caused by passing trains and vehicles is an important issue for the assessment of their influence on environmental impacts and engineering structures such as bridges, viaducts, historic architecture and residential buildings. The issue is complex because the nature of the soil is heterogeneous and the groundwater level changing depending on the season and this creates great difficulties in developing a theoretical model of vibration wave propagation. The paper presents developed numerical model of soil consisting of 4.3 million cubic finite elements based on the geological properties of soil. Developed model based on Drucker-Prager material model, which is often used in numerical methods for simulating the behaviour of different soil types. In addition, the material properties of the soil was specially prepared and allowed to use them directly in the material model used. Both concrete (building) and steel (plate forcing) were modelled using an isotropic material model. Element size was set at 300 mm. This value was determined by the adopted frequency range studied (0 to 100 Hz) and due to verification by simulation results of experimental studies in which excitation has been implemented in the frequency of 33 Hz (base frequency of excitation signal) and 66 Hz (second harmonic of excitation signal). The cut-off frequency 100 Hz defines a minimum wavelength propagated in the soil (based on the stiffness and density of the soil) and 10 finite elements was adopted at a wavelength, which is 3 meters to the ground, for the correct mapping of a sinusoidal waveform. Subsequently, experimental studies were performed to verify the model from which the conclusions are presented in the work. The work was carried out in a research project 4875/B/TO2/2010/38 financed by Ministry of Science and Higher Education.*

***Keywords:*** *finite element method, propagation of vibration wave in the soil, Drucker-Prager material model*

## 1. Introduction

The problem of vibrations wave propagation in the ground caused by railway vehicles and vehicles movement from the theoretical point of view is extremely complicated [6, 8]. This is mainly due to inhomogeneities in the land, its history and underground water dependent on atmospheric conditions. The consideration of problem of waves propagation based on the theory of surface waves propagation. This follows from the assumption that these waves destroy buildings and structures in earthquakes but can also cause devastating effects in the case of rail and road transport in the long-term duration of residential buildings in the vicinity of these roads as well as have a negative impact on human comfort placed in them. Propagation of vibration theory is described by the Rayleigh surface waves or by Love's waves when the elastic layer rests on the stiffer centre. Theoretically, surface waves are a number of special periodic solutions of the integral equation satisfying certain boundary conditions, i.e. the free edge of the elastic half-space. Hence, these solutions are characterized by wave velocity along the surface of the half-space and, what is their most important feature, fast fading amplitude with distance and depth from the surface. This disappearance is not due to attenuation but it is the specific effects of mutual longitudinal and shear waves. Such an approach to assess the propagation of vibrations in the ground and their impact on engineering structures is not very efficient, and therefore developed more practical theoretical methods of prediction of the vibrations wave propagations in the ground. These include Golitsyn method, the method of spreading the vibrations in the ground PN-80/B-03040 adopted and the method of numerical simulation in which the assumed earth model based on geological research [2, 3, 7, 9, 10]. This study includes experimental verification of simplified prediction method propagation of vibrations in the ground from the rail and road transport based on vibration examination conducted in a large urban centre.

## 2. Characteristic of waves propagation to the surroundings of the road

Variable dynamic loads caused by the movement of the vehicle generate waves that spread to the roadway surface and its neighbourhood (Fig. 1) [1].

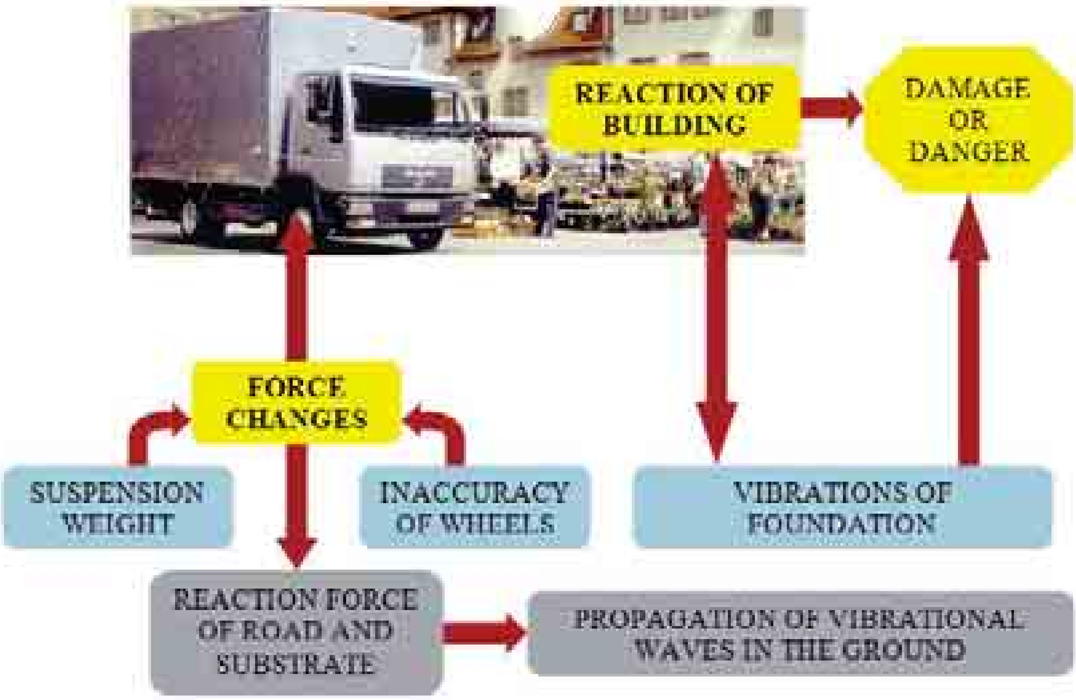


*Fig.1. Diagram of the wave vibration propagation in the environment*

Until now, the experimental studies are the most appropriate form of waves propagation in the ground examinations. Based on research can be assumed that the land has a natural frequency of vibration and for impulsive loads can spread vibrations of this frequency. The frequencies corresponding to the maximum amplitude depend on the characteristics of the land and the mass and mechanical properties of the calling vibration, the load distribution and the interaction system: the vehicle - road - substrate. Construction of roads and the stratification of soil heterogeneity that occur in the vicinity of the road and cause the waves generated by the wheel contact with the road are complex. At the junction of roads and soil layers followed by reflection, refraction and interference, so that in the vicinity of the road is not possible to distinguish the type of waves. The components of the individual waves propagate at different speeds, their components show a complex course of the phenomenon, and therefore assumed to call them surface waves in contrast to the Rayleigh waves and their distribution pattern is exactly as described in the literature. Surface waves are characterized by the fact that they have a lower velocity of seismic waves of longitudinal and transverse, have a greater amplitude but is much faster suppressed. One can identify different types of waves during the measurements of ground vibrations after the i.e. explosion or earthquake.

Small oscillations of the longitudinal waves are first, then one can identify small oscillations of the transverse waves and at the end the surface waves with large amplitudes.

Velocity of propagation of a particular type of waves is determined by the equations:

– longitudinal waves:

$$v_l = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}\,, \tag{1}$$

– transverse waves:

$$v_t = \sqrt{\frac{E}{2(1+\nu)\rho}} = \sqrt{\frac{G}{\rho}}\,, \tag{2}$$

– surface waves:

$$v_s = 0.96\,v_t = \sqrt{\frac{G}{\rho}}\,, \tag{3}$$

where:
$E$ – Young's modulus,
$\nu$ – Poisson's ratio,
$\rho$ – density.

Another important issue is to assess the actual course of ground vibration. The research shows that the curve is characterized by changes in the size of amplitude with distance is regular in the case of a homogeneous medium, and disrupted the layered substrate. When activated by groundstrokes – vertical vibrations of surface momentum going into a group of waves whose amplitude vanishes in both time and distance-call stroke. Based on work [1] should be expected with the highest level of vibration in the case of transit vehicle with a trailer, it should add up vibrations from the car and trailer. If you are close to each other goes a few vehicles, their impact on the level of the excited vibrations may overlap, which in turn can lead to several times increase of the level of vibrations induced .by a single vehicle.

This hypothesis is difficult to prove and not supported by the operating results of the measurements, as you can imagine, based on the geometry of the submission of vibration, that vibration from several vehicles are mutually suppressing. Our study confirmed that vibrations caused by passing several vehicles at the same time, it does not cause a rapid increase in the level of vibration, and in some cases were smaller than the one run. In general, based on the research can be stated that a major impact on reducing the level of vibrations that spread to the surrounding roads to stabilize the road surface on which effect is influenced by structural friction (energy dissipation) between the elements stabilizing the soil. It is concluded that for stabilization of the substrate, the contact force (tire-surface) move not only on the rigid system, but also on a larger surface of the ground, reaching to the deeper, stronger and less compressible substrates. The highest level of vibration can be expected after crossing the road with the ground clay and gravel of the smallest on the way. Change of vehicle speed from 30 to 50 km / h slightly affects the level of ground vibration. As we can see, the mechanism of transmission of vibration is very complicated for several reasons. The most important reasons are:

– significant changes in material properties due to changes in roadway atmospheric,
– road viscoelastic properties (complex module depends on the local stress load and speed).

All these factors make the current lack of accurate methods for the description of the vibration transmission path in the environment.

### 3. Prognostic assessment of vibration propagation based on simplified methods

The forecast of the spread of the vibration from the road, tram-car on a residential building which is at the stage of the project was initially based on Polish Norm PN-80/B-03040, then verified by the Golitsyn method and finally verified by numerical simulation of the vibration propagation for the same conditions .

### 3.1. Prognostic assessment of vibration propagation based on Polish Norm PN-80/B-03040

According to the model adopted in the standard vertical vibration amplitude (horizontal) ground $A_r$ ground at a distance $r$ (Fig. 2) from the centre of gravity of the foundation (in our case the subgrade tram) caused by the vertical (horizontal) forced vibrations of the foundation may be an indication, regardless of the type of ground surface, designated by relationship:

$$A_r = A_0\,\rho\,, \tag{4}$$

where:
$A_0$ – amplitude of vibrations caused by passing trams,
$A_r$ – amplitude vibrations of the ground at a distance r from the axis of track,
$\rho = \sqrt{\dfrac{1}{\beta} - 0.4\left[\dfrac{1}{\beta} - \left(\dfrac{1}{\beta}\right)^2\right]}$,
$\beta = \dfrac{r}{r_0}$,
$r_0 = \sqrt{\dfrac{F}{\pi}}$,
$F$ – surface of a single primer.

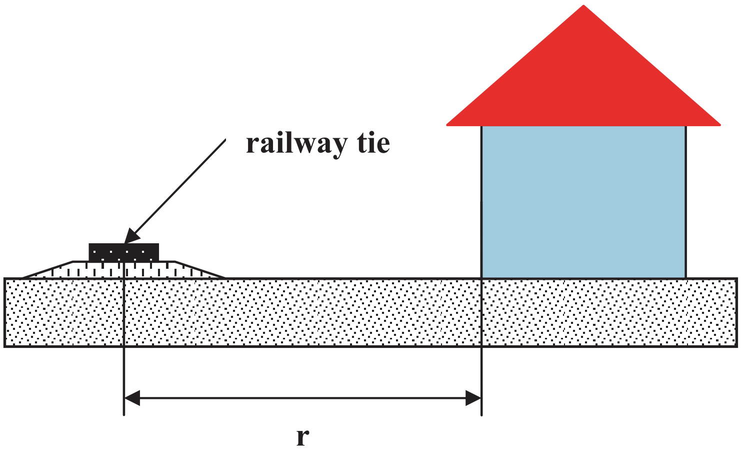


*Fig. 2. The computational model used in the analysis of wave propagation in the ground*

Assuming that the distance from the foundation of an newly designed apartment building from the axis of single track r is equal to 20 m, the surface of a single railway tie $F$ is equal to 0.51 m$^2$, we calculate the $r_0$ = 0.4 m, $\beta$ = 50. Substituting these values into equation 2, we determine the coefficient $\rho$, which is 0.133. Assuming further that the amplitude of the excitation $A_0$ of a single tram journey, measured on the backing of about 1 m/s$^2$ (these data should be verified by measuring –search has shown 0.77 m/s$^2$ for the tram NGT6 – may be higher depending on the condition of tracks, type of tram, the vibration isolating security, etc.), then the value of the amplitude of vertical and horizontal set theory (in the building they play a major role, although the vertical vibration can cause adverse subversive moment) transferred to the projected residential building are $A_r$ = 0.133 m/s$^2$.

According to section 4.3 of Polish Norm PN-85/B-02170, effects of vibration transmitted by the base of the building can be omitted in those cases where the share of the burden of the structure is negligible and indicative can be assumed that the amplitude of horizontal ground motion acceleration at the foundation of the building satisfies the condition $a_p$ < 0.005 g.

### 3.2. Prognostic assessment of vibration propagation based on Golitsyn method

The verification of this forecasting method was based on the relationship given by Golitsyn, with errors, but estimates for this type of vibration sufficiently convenient and simple to use, point [2]. Moreover, bearing in mind the possibility of interference during the construction of a newly designed building through the use of properly selected isolation level security such as vertical or road or rail car, you can effectively protect the surrounding environment from the effects of road transport, tram-car. This relationship is as follows:

$$A_r = A_0 \sqrt{\frac{r_0}{r}}\, e^{-\alpha (r - r_0)}, \tag{5}$$

where:
$A_0$ – amplitude of vibrations caused by passing trams (Fig. 2),
$A_r$ – amplitude vibrations of the ground at a distance r from the axis of track (Fig. 2),
$\alpha$ – dissipation ratio of vibrational energy.

The allowable amplitude of acceleration, which allows for the omission of the forces of inertia in the building, determined on the basis PN-85/B-02170 – "Evaluation of harmful vibrations transmitted by the base of buildings". Its value to determine the vibration zone was adopted for both horizontal directions ($x$, $y$) and for the vertical direction ($z$) equal to $A_r = 0.005$ g Assuming then the value of absorption coefficient $\alpha = 0.03$ (weak, saturated with water, small and medium-sized and silty sands, sandy clay and clay can determine the distance $r$ acting in the zone of maximum amplitudes of vibration. for example, assuming the forecast of the spread of the vibration amplitude of the maximum value of acceleration equal to $A_0 = 1.00$ m/s$^2$, which were measured (these data should be verified by measurement – survey showed 0.77 m/s$^2$ for the tram NGT6 – may be higher depending on the condition of tracks, a streetcar, vibration isolating security, etc.) on the tram route Kraków can be determined theoretically the spread of vibration for the same class of roads. this is done by transforming the equation (3) the following form:

$$B = \frac{1}{r}\, e^{-2\alpha r} = \frac{1}{r_0\, e^{2\alpha r_0}} \cdot \left(\frac{A_r}{A_0}\right)^2. \tag{6}$$

The solution of equation (6) can be determined by the graphical method. For example, assuming the following values: $r_0 = 5$ m, $A_r = 0.04$ m/s$^2$, $A_0 = 1.25$ m/s$^2$ and solving them as a function of the absorption coefficient α for which, the following values: $\alpha = 0.01$ ( weak, saturated with water, small and medium-sized and silty sands, sandy clay and clay), $\alpha = 0.04$ (medium and coarse sand and wet clay and clay), $\alpha = 0.1$ (sandy clay, clay and silt little wet and dry). Roots of the equation (6) provide for such a distance in the input parameters, which should draw the line vibration zone. In Fig. 3, 4 and 5, shows how it affects the zone of vibration energy absorption coefficient $\alpha$. Roots of equation (6) are $r(\alpha) = \{172 \text{ m}, 61 \text{ m}, 31 \text{ m}\}$, which means that at this distance should draw the line vibration zone. Based on this analysis it is clear that the effect of the absorption coefficient on the width of the zone is very large. Based on it and information about the surface geology of the land area can be determined vibration over the whole route of the proposed road car. Of course, in practice, the distance is much smaller area for many reasons such as soil heterogeneity, and the road runs on an embankment or in the trench, the presence of drainage ditches along the road, etc.

Since the proposed road route can take place near existing residential buildings that are located at a shorter distance than the limit designated zones, you can reverse the problem, i.e., assume that all the buildings in the distance r less than 25 m, generally should be protected, then we assume that the border zone of vibration is 25 m, then transforming the relationship (5) we can determine the allowable amplitude of excitation on the gauge of the road. Equation (5) takes the following form:

$$A_0 = A_r \sqrt{\frac{r}{r_0}}\, e^{\alpha (r - r_0)}. \tag{7}$$

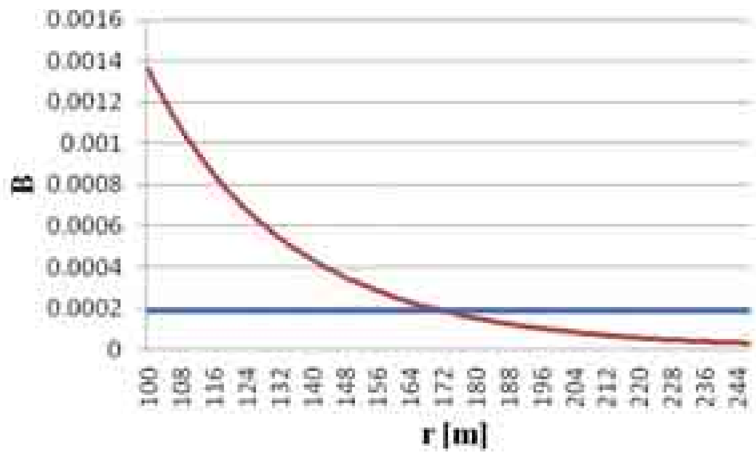


*Fig. 3. Radius of vibrational zone for the α=0.01*

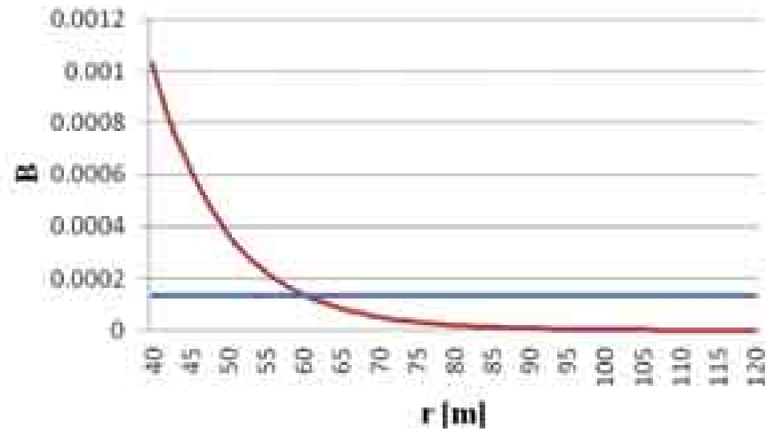


*Fig. 4. Radius of vibrational zone for the α=0.04*

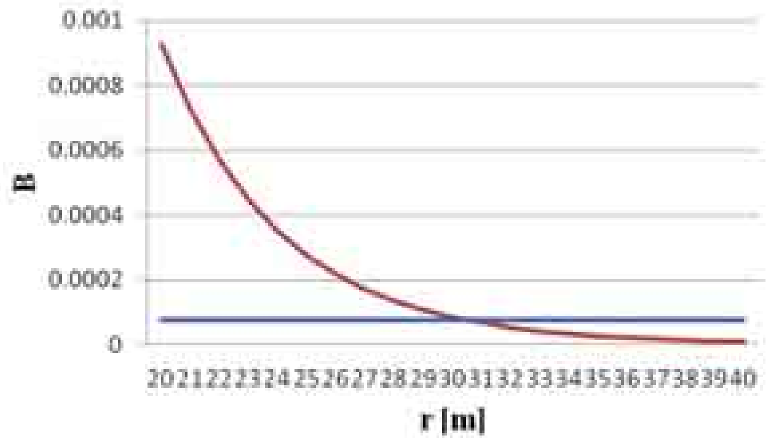


*Fig. 5. Radius of vibrational zone for the α=0.10*

Substituting the above equation the following data: $r = 25$ m, $r_0 = 5$ m, $A_r = 0.04$ m/s$^2$, we will limit the amplitude as a function of the roadway gauge the soil type (factor absorption – $\alpha$), which are:

- for $\alpha = 0.01$ – $A_0 = 0.10$ m/s$^2$,
- for $\alpha = 0.04$ – $A_0 = 0.13$ m/s$^2$,
- for $\alpha = 0.10$ – $A_0 = 0.24$ m/s$^2$.

The overall conclusion is that there are two possibilities to develop forecasts of vibration zones designed to protect against the influence of vibration on the environment. The first is the appointment of vibration zones, with the knowledge of the geological data of the land, but the area is very wide, in the sense of the border zone, which is associated with an increased number of buildings that should be protected. The second possibility is the imposition of such zones within 25 m and defining the permissible amplitudes of accelerations or displacements on the road gauge in the case of isolation, the values of the amplitudes of acceleration or displacement, ground vibration that is mounted Vibration isolation. In this case, reduces significantly the number of buildings that should be protected, and limit the amplitude can be obtained with vibration isolation performance of the road or the road having a solid foundation even exchange of land.

### 3.3. Prognostic assessment of vibration propagation based on numerical simulation

Computational model consists of a cuboid with dimensions of 30x19x4 m (Fig. 6) which was built with the following elements [4]:

- UIC60 tracks were modelled with beam elements with rectangular cross-section,
- railway ties PS-83 were modelled with eight-node solid elements in a 670 mm scale,
- stony ballast of 300 mm thickness below the railways ties was modelled with four-node solid elements. Between the ballast and the tracks there was no contact,
- subgrade of 300 mm thickness was modelled with four-nodes solid elements,
- soil was modelled with four-nodes solid elements,
- sidewalk of 50 mm thickness was modelled with four-nodes solid elements,
- fragment of the building was modelled with four-node solid elements.

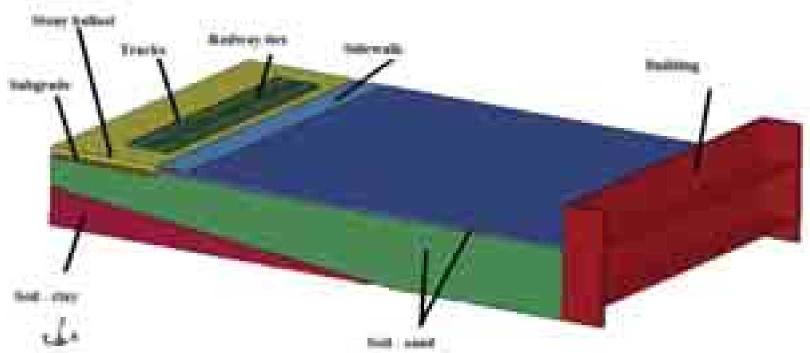

*Fig. 6. Diagram of computational model*

A numerical simulation of the foundation vibration of newly designed building was carried. The results of this analysis for points located at the foundation of 1 m above the ground and 2 m below the ground surface in the direction of X and Y axes are shown in Fig. 7 and 8.

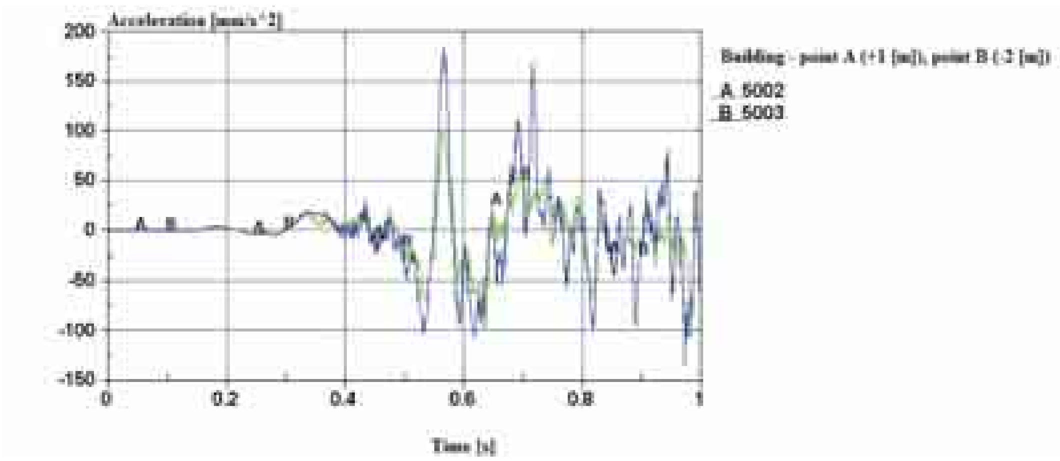


*Fig. 7. Amplitude of the vibration acceleration of the foundation of the building in the X direction*

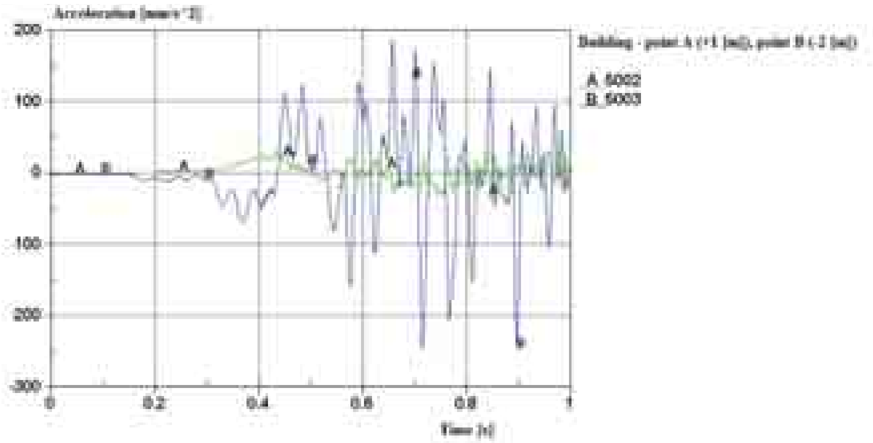


*Fig. 8 Amplitude of the vibration acceleration of the foundation of the building in the Y direction*

The results (Fig. 7 and 8) can be concluded that the amplitude of vibration acceleration in X and Y axes exceed the limit values. The simulation results showed that the amplitudes of vibration acceleration of foundations of newly designed buildings that exceed the value of 0.005g and the propagation of vibration wave should be take into account during the design process of building [5, 11].

## 4. Experimental verification of waves propagation in the ground

Based on recorded during the test verification of vibration time signals on a single measurement of cross-sections through a large urban area for the analysis of selected passages involving the transportation trams and automobile communication. The graphs presented in Fig. 9, 10 and 11 show the vibration spectra determined from the amplitude of time histories of ground vibrations.

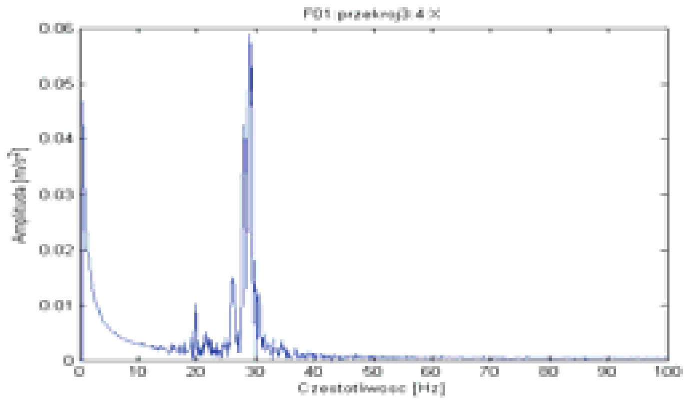


*Fig. 9. The spectrum of the acceleration of the building in the X direction*

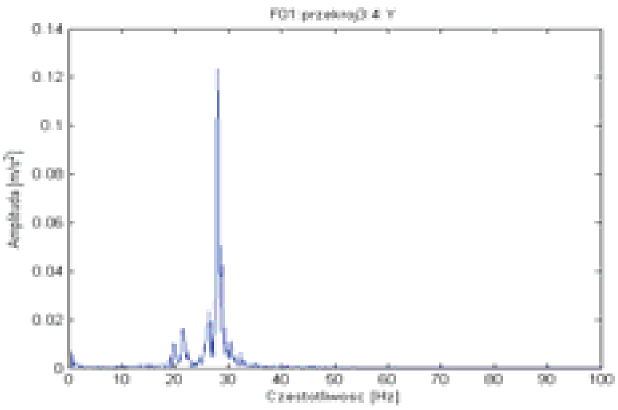


*Fig. 10. The spectrum of the acceleration of the building in the Y direction*

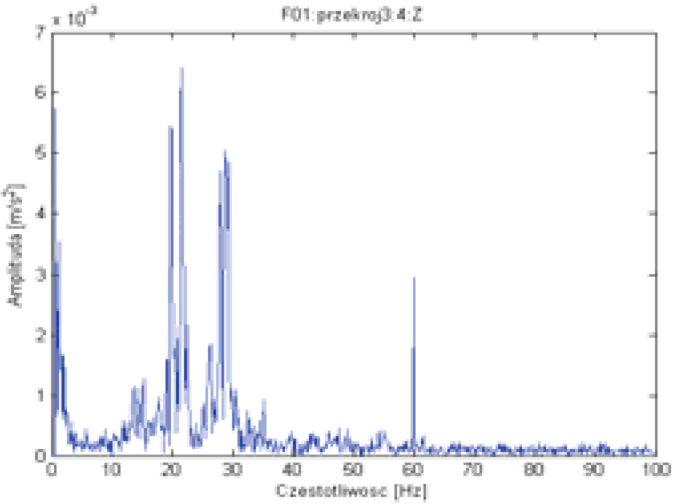


*Fig. 11. The spectrum of the acceleration of the building in the Z direction*

## 5. Conclusion

Based on considerations it can be stated that none of the methods of forecasting spreads the vibration in the ground is not fully reliable. Although each of them indicated a significant effect on risk of newly designed building shake, but significantly differed from the values obtained by experiment. Hence, it is concluded that the essential building a database of extortion, creating numerical models of various types of vibration waves emanating from rail and road transport should be carried out with many experiments.

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