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Original article

The use of modelling of impacts exerted by means of transport on the environment for ensuring safety

***Joanna Bril**[*1]**, Edward Rydygier**[2]*

[1] Higher School of Podkarpacie in Jasło,
joannabril@vp.pl

[2] Municipal Office of Warsaw (Urząd m. st. Warszawy),
erydygier@gmail.com

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* Corresponding author

ABSTRACT

The article presents the model research on impacts exerted by means of transport on the structures. In modelling the dynamics of transport systems the dynamic properties of the ground forming the foundation soil for tracks or roadways have been taken into account. The ground has been modelled as an elastic half-space. The dynamics of an infinite mass band being in contact with an elastic half-space has been investigated. As part of the research on impacts exerted by means of transport on structures a model of a problem has been examined where an automotive vehicle, representing a concentrated force in motion, is in contact with a roadway described as a rigid body coupled with an elastic half-space. It has been demonstrated that a surface (Rayleigh) wave propagates in the ground, being a continuous (elastic) medium, and acts on a structure modelled as a rigid body. The research results have been presented in the form of vertical and horizontal transmittances of the ground for different frequencies of loading with different unit forces.

KEYWORDS

means of transport, dynamics of transport systems, elastic foundation

1. Introduction

The civilisation development and use of modern means of transport make it necessary to determine their influence on the municipal infrastructure, technological processes and the natural environment. Air pollution caused by the use of fossil fuels, noise and vibrations exert an adverse influence on the environment and human life. This paper presents the model research on transmission of vibrations from their sources, represented by vehicles moving on the roads, to the road structures (underground and above-ground). The core element of the research is the modelling of transport system dynamics, taking account of the dynamic properties of the soil forming the subgrade for rails or roads.

In this paper the research on impacts exerted by means of transport on the structures has been conducted on the basis of a modelled problem where a vehicle, in the form of a concentrated force in motion, is in contact with a roadway, in the form of an infinite mass band coupled with an elastic half-space. The Rayleigh wave propagates in the ground, being a continuous (elastic) medium, and acts on a structure modelled as a rigid body, interacting with an elastic half-space.

2. Effects of means of transport on the environment

2.1. Threats to human life and the natural environment

As the civilisation develops, the man's need for moving around grows. This need is being satisfied by easily accessible, cheap and increasingly comfortable transport solutions. Unfortunately, the development of transport is accompanied by side effects, influencing adversely the natural environment and human life. Because of the use of fossil fuels to propel means of transport the hazard caused by air pollution, harmful to human health, increases. The European Environment Agency reports that transport accounts for 24% of carbon dioxide emissions, out of which 84% of such emissions are attributable to road transportation [Bril and Lukasik 2013]. The CO_2 emission caused by transport increased by 15% between the years 2000 and 2008. Vehicle exhaust gases represent the greatest source of air pollution and they are more harmful to humans than any pollution of industrial origin, as automotive pollution spreads in high concentrations at low altitudes in the immediate vicinity of places where there is human habitation. According to the studies, in tunnels, multi-storey car parks and near refilling stations the concentration of pollutants is sometimes from four to 40 times higher than the average for the whole urban area [Lukasik et al. 2013]. The research conducted in London showed that the concentration of some pollutants is several times higher inside a vehicle than the concentration outside [Bril and Rydygier 2014]. Therefore, after travelling a certain distance in the city by car the driver has a higher carbon dioxide concentration in blood than the cyclist who has ridden the same distance.

Another hazard for humans is the noise generated by traffic. Road traffic noise accounts for almost 80% of all acoustic hazards in the environment. In Poland, nine million inhabitants of cities and four and half million inhabitants of rural areas are exposed to road traffic noise and one million people are exposed to railway traffic noise [Bril and Rydygier 2013]. Sounds generated by moving vehicles in the form of noise may have harmful effects in humans by:

- acting on the hearing organ and causing the feeling of nuisance or hearing loss,
- eliciting a response from the autonomic nervous system in the form of changes to perfusion in respective organs of the human body.

Apart from noise, means of transport generate vibrations. Vibrations propagating to buildings located near transport routes are particularly onerous for their inhabitants, since the natural frequency of such buildings and forced vibration frequency are similar. Vibrations induced by rail or road vehicles propagate in the soil medium, acting on structures, such as tunnels, bridges and foundations of buildings. In such medium two types of waves can occur, propagating with different velocities: longitudinal, irrotational, dilatation P (from primary wave) waves, and transverse rotational, distortion S (from shear wave) waves, and also surface R waves (Rayleigh type). Their characteristic feature is decaying as they travel deeper into the layer. One of the reasons for the decay of wave amplitude with an increase in distance is the dissipation of wave energy in the elastic half-space, in connection with the increasing wavefront. The other reason for the decreasing wave amplitude with an increase in the distance from its source is the energy loss in the ground caused by the phenomenon of absorption, related to the ground inelasticity (viscosity). Experimental studies show that the ground has filtering properties. Wave components of higher frequencies are absorbed to a greater extent than low frequency components, which, consequently, affects the shape of the wave. To reduce the vibration effects on buildings active and passive vibration isolation is used. The appropriately designed track structure is one of the main factors contributing to the reduction of vibrations produced at the source, and to this aim unconventional track structures are used [Strzyzakowski 2007].

2.2. Foundation soil

The foundation soil is related to all types of buildings and structures that are used in practice. In the railroad engineering the foundation soil is represented by a trackbed, whereas in the road transport it is the soil under and around the road surface (roadway). The basic task fulfilled by a trackbed is to receive various types of loads acting on the rail. The foundation soil is a construction material, for example in an embankment, however, at the designing stage the real medium should be modelled as an elastic foundation.

In the model research presented in this article, taking account of the dynamic properties of soils, the soil has been modelled as an elastic half-space [Alsaidi et al. 2014; Ataman 2014]. It has been considered that the model of an elastic half-space demonstrates the interaction between load and the soil in a better way than the model of a Winkler type soil, which disregards wave effects [Szczesniak 1995]. Apart from that, despite its simplicity in the mathematical description (system of unconnected massless springs placed on the stiff base), a Winkler model renders it difficult to determine in practice the value of soil stiffness. In the mathematical description of loading of the elastic half-space the investigated system has been described in two dimensions (2D system).

2.3. Models of vehicle-track systems, taking account of the foundation soil

Model solutions of impacts exerted by a vehicle on the track or road surface, taking account of the dynamics of soil modelled as an elastic half-space, include interactions between soils and discrete systems of different contact geometries. The research focused on the system consisting of an oscillator and a half-space with a circular contact, an infinite band having a displacement interface with an elastic half-space, and also the model of a concentrated load interacting with a viscoelastic half-space [Bril et al. 2016; Strzyzakowski 1989; Strzyzakowski 1992; Strzyzakowski 2007].

From among various models of rail-vehicle-track (road vehicle – road surface) systems, the dynamics of the system forming an infinite rigid band, of the width of 2*a*, that has a displacement interface with an elastic half-space (Fig. 1) has been investigated. The coordinates x_1, x_2 are related to the perpendicular axes on the boundary plane of the half-space, where the coordinate axis x_2 is located along the band length and the coordinate axis x_3 is perpendicular to the boundary plane. A vertical load $P(t)$ is applied to the band with the mass m.

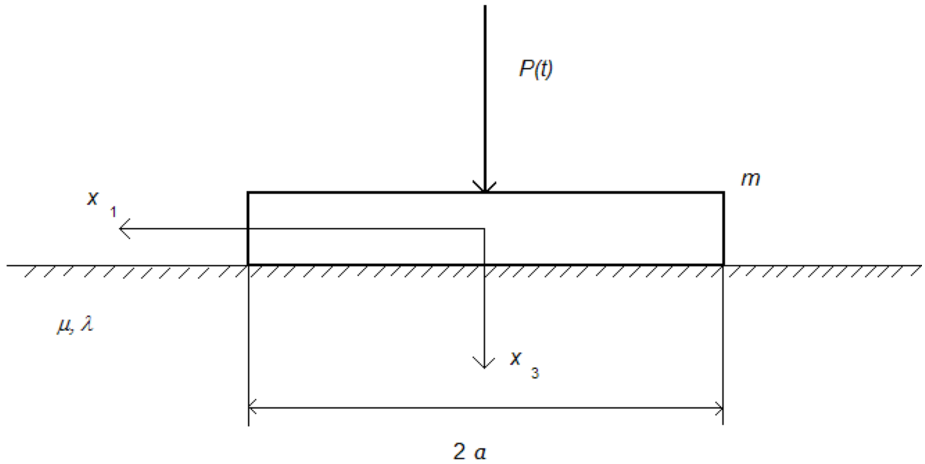

Fig. 1. Infinite rigid band system in contact with an elastic half-space
Source: own work.

The equation for vertical motion of a band using the frequency notation is as follows [Strzyzakowski 2007]:

$$R(\omega) = m\omega^2 u_3(0,0;\omega) + P(\omega) \tag{1}$$

where:

- $R(\omega)$ – Fourier transform of a soil reactive force,
- $u_3(0,0;\omega)$ – vertical soil displacement,
- $P(\omega)$ – Fourier transform of a loading force applied to the band.

For the investigated system the equation for soil motion is based on the equation for medium motion, from the theory of elasticity (Lame's equation), which in the vector form is as follows [Dylag et al. 1999].

$$a_1^2 grad\ div\ \vec{u} - a_2^2 rot\ rot\ \vec{u} = \frac{\partial^2 \vec{u}}{\partial t^2}, \qquad x_3 \geq 0, \tag{2}$$

where:

$\vec{u}(u_1, u_2, u_3)$ – displacement vector in an elastic half-space,

$a_1^2 = \frac{2\mu+\lambda}{\rho}$, $a_2^2 = \frac{\mu}{\rho}$, λ, μ – Lame's elastic constants, ρ – soil density.

Boundary conditions for the band – half-space interface for: σ_{33} – normal stress, σ_{13} – shear stress, have the following form:

$$\sigma_{33} = \begin{cases} \frac{R}{2a} & -a\langle x_1 \langle a, \quad x_3 = 0 \\ 0 & |x_1|\rangle a \quad , \quad x_3 = 0 \end{cases}, \qquad \sigma_{13} = 0 \qquad x_3 = 0. \tag{3}$$

The boundary conditions on the surface of the elastic half-space have been determined from the constitutive equation, taking account of the influence exerted by material properties on the relationships between stresses σij and strains εij [Gabryszewski 2001], which in the case of an isotropic elastic body has the following form: σij = λεkkδij + 2μεij, and then, taking into consideration the geometric relationship $2\varepsilon_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}$, it is possible to determine $\sigma_{33} = \lambda div\vec{u} + 2\mu\frac{\partial u_3}{\partial x_3}$ and substitute it into equation (3).

The solution for a flat problem of boundary values (2) and (3) in the coordinates x_1, x_3, after Bessel-Fourier inverse transform has been applied, has the following form [Evans 2002; Potter 1980]

$$u_3(x_1,x_3;\omega) = -\frac{1}{\mu}\gamma_3(x_1,x_3;\omega)R(\omega), \tag{4}$$

where:

γ_3 – transfer function in an integral form, was provided in article [Strzyzakowski 2007].

For $x_1 = x_3 = 0$ on the basis of equations (1) and (4) it is possible to determine

$$u_3(0,0;\omega) = \frac{\frac{1}{\mu}\gamma_3(0,0;\omega)}{1-\frac{m\omega^2}{\mu}\gamma_3(0,0;\omega)}P(\omega). \tag{5}$$

Taking into account the approximate form of the transfer function $\gamma_3(x_1,0;\omega)$ corresponding only to a surface wave (provided in article [Strzyzakowski 2007]), and assuming that $x_1 = 0$ the natural frequencies of the system have been determined by equating the denominator of expression (5) to zero

$$1 - \beta z(\alpha_1 e^{-iz} + i\alpha_2) = 0, \tag{6}$$

where:

$$\beta = \frac{m}{\mu}\frac{a_1^2 a_R^2}{a^2}, \quad z = \omega\frac{a}{a_1 a_R}, \quad \alpha_1 = \frac{c_2\left(2-c^2a_R^2\right)^2\sqrt{1-a_R^2}}{16\left(c^2-1\right)-8c^2a_R^4+2c^8a_R^6}, \quad \alpha_2 = \frac{1}{c^2a_R^2}, \quad c = \frac{a_1}{a_2},$$

a_R – phase velocity of a surface wave (having the value of 0.5 for typical soils).

After the substitution of frequency in a complex form $z = z_1 + iz_2$ into expression (6), the obtained solution is in the form of relationships $z_1(z_2)$ and $z_2(z_1)$ describing the curves which at the point of intersection determine the natural frequencies, being sought, of the system. For the parameters α_1, α_2, a_R of the real soil the roots of equation (6) can be presented as follows

$$z_1 = \sqrt{-\left(-\frac{1}{\alpha_2\beta}+\frac{1}{\alpha_1\beta}\frac{1}{\frac{\alpha_2}{\alpha_1}-e^{\frac{1}{\alpha_2\beta}}}\right)\left(-\frac{1}{\alpha_2\beta}+\frac{1}{\alpha_1\beta}\frac{1}{\frac{\alpha_2}{\alpha_1}+e^{\frac{1}{\alpha_2\beta}}}\right)}, \qquad z_2 = -\frac{1}{\alpha_2\beta}, \tag{7}$$

$$\alpha_1 > 0, \qquad \alpha_2 > 0.$$

If the natural frequency, being sought, is sufficiently small $|z| << 1$, which means that $e^{-iz} \approx 1$, then from equation (6) the following can be obtained: $z = \frac{1}{\beta}\frac{\alpha_1}{\alpha_1^2+\alpha_2^2} + i\frac{1}{\beta}\frac{\alpha_1}{\alpha_1^2+\alpha_2^2}$, based on which the vibration frequency f ($\omega = 2\pi f$) is as follows

$$f = \frac{\mu a}{2\pi m a_R}\frac{\alpha_1}{\alpha_1^2+\alpha_2^2} + i\frac{\mu a}{2\pi m a_R}\frac{\alpha_1}{\alpha_1^2+\alpha_2^2}, \tag{8}$$

where:

μ – Lame constant,

$2a$ – band width,

a_R – phase velocity of a surface wave,

m – linear density of the band mass.

3. Impacts exerted by means of transport on the structures

3.1. Dynamics of the examined system

As part of the research on impacts exerted by means of transport on structures the model of a problem has been considered, where a road vehicle is in contact with the roadway described as a rigid body having, at its central point, a displacement-based coupling with the elastic half-space. In the ground, being a continuous (elastic) medium, the surface wave (Rayleigh wave) propagates, acting on a structure modelled as a rigid body, which interacts with this half-space [Strzyzakowski 2007].

The problem under consideration can be approached from the spatial perspective, but because of the complexity of calculations a flat problem has been adopted for modelling purposes. It has been assumed that the contact between the rigid body, representing the building foundation, and the ground is of such nature that their displacements are equal. It has been assumed that the lateral dimensions of the structure are small in comparison with the length of the Rayleigh wave propagating on the surface. It means that there is a point contact between the body and the half-space, which is tangential with respect to displacements and continuous with respect to stresses. The coordinate axis x_1 is located on the boundary plane, in the direction set by the width of the roadway, the axis x_2 is also located on the boundary plane and it is perpendicular to the axis x_1, whereas the axis x_3 is perpendicular to the boundary surface (Fig. 2).

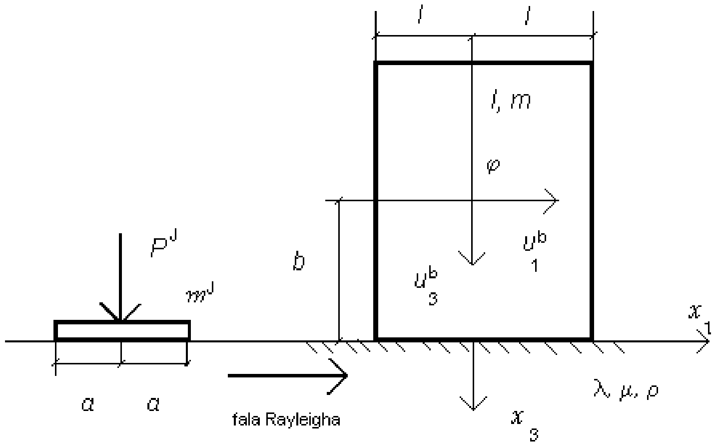

Fig. 2. Vehicle and structure system

Source: own work.

The equations for body motion in a flat problem in the coordinates x_1, x_3 in the frequency notation have the following form [Strzyzakowski 2004]

$$-m\omega^2 u_1^b + R_1 = P_1^z, \qquad -I\omega^2\varphi + bR_1 + M = M^z, \tag{9}$$

$$-m\omega^2 u_3^b + R_3 = P_3^z,$$

where:

u_1^b, u_3^b	– body displacements, horizontal respectively
P_1^z, P_3^z, M^z	– external loads,
R_1, R_3, M	– soil responses,
ω	– frequency,
m, I	– body parameters,
b	– height of the centre of gravity of the body.

The soil responses R_1, R_3, M can be determined from the boundary value problem for the equation of soil displacement motions, being Lame's equation, which has the following form in the operator notation [Dylag et al. 1999; Gabryszewski 2001]

$$a_1^2 \nabla\nabla \vec{u} - a_2^2 \nabla\times\nabla\times \vec{u} = \frac{\partial^2 \vec{u}}{\partial t^2}, \tag{10}$$

where:

a_1^2 – square of longitudinal wave velocity,

a_2^2 – square of transverse wave velocity,

∇ – *nabla* operator.

The boundary values for a flat problem in the coordinates x_1, x_3 at the structure width of $2l$ (along the coordinate axis x_1) are as follows

$$\sigma_{33} = \begin{cases} \frac{R_3}{2l} + \frac{3}{2}\frac{M}{l^3}x_1 & -l\langle x_1 \langle l \\ 0 & |x_1|\rangle l \end{cases}, \qquad \sigma_{13} = \begin{cases} \frac{R_1}{2l} & -l\langle x_1 \langle l \\ 0 & |x_1|\rangle l \end{cases} \tag{11}$$

The solutions for a boundary value problem (10), (11) for the components u_1, u_3 of soil displacement are as follows

$$u_1(x_1, x_3;\omega) = \frac{1}{\mu}\gamma_{11}(x_1,x_3;\omega)R_1 + \frac{1}{\mu}\gamma_{13}(x_1,x_3;\omega)R_3 + \frac{1}{\mu}\gamma_{1\varphi}(x_1,x_3;\omega)M + u_1^P(x_1, x_3;\omega),$$

$$u_3(x_1, x_3;\omega) = \frac{1}{\mu}\gamma_{31}(x_1,x_3;\omega)R_1 + \frac{1}{\mu}\gamma_{33}(x_1,x_3;\omega)R_3 + \frac{1}{\mu}\gamma_{3\varphi}(x_1,x_3;\omega)M + u_3^P(x_1, x_3;\omega), \tag{12}$$

where:

γ_{11}, $\gamma_{13} = -\gamma_{31}$, γ_{33}, $\gamma_{1\varphi}$, $\gamma_{3\varphi}$ – transfer functions in an integral form provided in article [Strzyzakowski 2007],

u_1^P, u_3^P – coordinates of the vector of externally applied soil displacements resulting from the operation of means of transport.

At the point of contact $x_1 = x_3 = 0$ the following relationships occur

$$u_1^b(0,0;\omega) = u_1(0,0;\omega), \qquad u_3^b(0,0;\omega) = u_3(0,0;\omega), \qquad \varphi = \frac{\partial u_3}{\partial x_1}(0,0;\omega), \tag{13}$$

which substituted into system of equations (12) make it possible to determine the unknown R_1, R_3, M. The lack of external forcing has been assumed $P_1^z = P_3^z = M^z = 0$. Article [Strzyzakowski 1989] showed that at the point of contact $\gamma_{13} = \gamma_{31} = \gamma_{3\varphi} = \gamma_{31,1} = \gamma_{33,1} = 0$. The determined displacements of the structure have the form of

$$u_1^b = \frac{R_1}{m\omega^2}, \qquad u_3^b = \frac{R_3}{m\omega^2}, \qquad \varphi = \frac{1}{I\omega^2}\left(M + bR_1\right). \tag{14}$$

3.2. Roadway and soil system

The roadway and soil system has been described as a rigid body having a displacement-based contact with the soil at its centre point and making vertical motions under load resulting from the operation of road transport vehicles (Fig. 3).

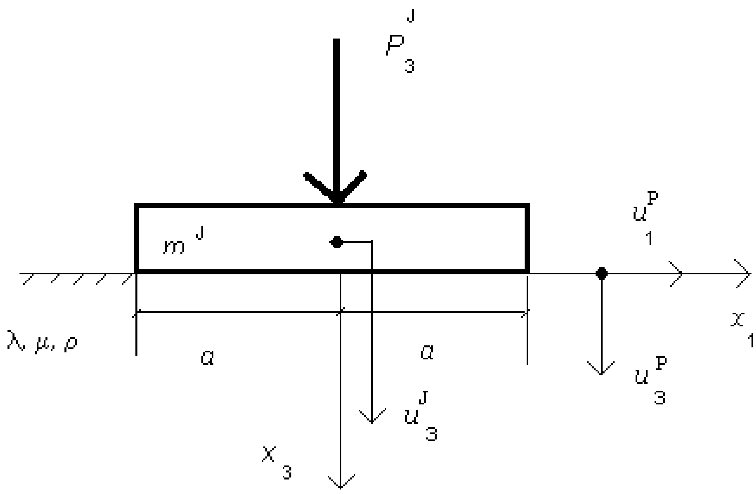

Fig. 3. Roadway and soil system
Source: own work.

In this case the modelling is similar to the one used for the loading of the half-space with the infinite mass band of the width of 2a. The motion equation for the roadway displacement u_3^J at the load P_3^J and the mass m^J for a flat problem in the frequency notation is as follows [Strzyzakowski 2007]:

$$R_3 = m^J \omega^2 u_3^J(0,0;\omega) + P_3^J \tag{15}$$

Displacements in the coordinates u_1, u_3 in the elastic half-space have the form of

$$u_3(x_1,0;\omega) = \frac{\frac{1}{\mu}\gamma_{33}(x_1,0;\omega)}{1-\frac{m^J\omega^2}{\mu}\gamma_{33}(0,0;\omega)} P_3^J = t_3 P_3^J, \tag{16}$$

$$u_1(x_1,0;\omega) = \frac{\frac{1}{\mu}\gamma_{13}(x_1,0;\omega)}{1-\frac{m^J\omega^2}{\mu}\gamma_{33}(0,0;\omega)} P_3^J = t_1 P_3^J, \tag{17}$$

where:

t_1, t_3 – transmittances of soil displacement, horizontal and vertical, respectively.

3.3. Research results

The plotted squares of the transmittance module t_3 at $x_1 = 0$ for three values of the roadway mass are presented collectively in Figure 4.

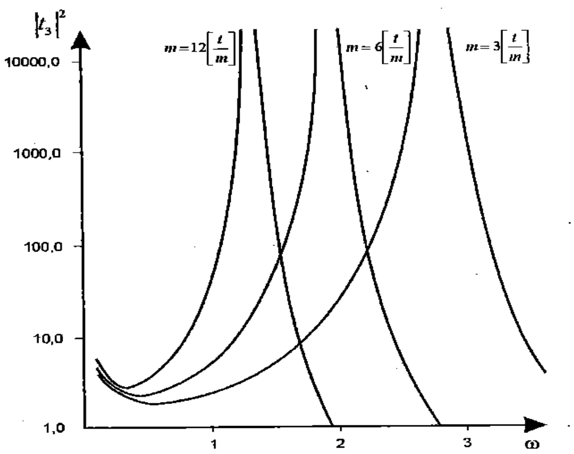

Fig. 4. Square of the transmittance module of the vertical displacement of the roadway
Source: [Bril et al. 2016].

The graphs presented in Figure 4 define the value of natural frequency of the roadway and its damping value and indicate that the roadway vibrations are of a single-mode nature. The displacements of the structure u_1^b, u_3^b, φ at different frequencies of forcing applied to the roadway with unit force can be determined using formulas (14). For the data [Strzyzakowski 2007]:

c = 3,0, a_1 = 1000 [m/s], a = 6,0 [m], l = 5,0 [m], b =5 [m],

m = 5 10^4 [kg], I = 3,5 10^6 [kg m^2], m^J = 1200 [kg].

The selected results are presented in Figures 5 and 6.

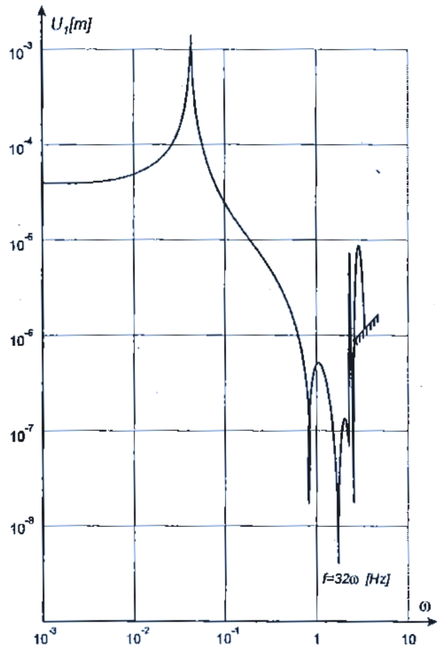

Fig. 5. Horizontal displacement
Source: [Bril et al. 2016].

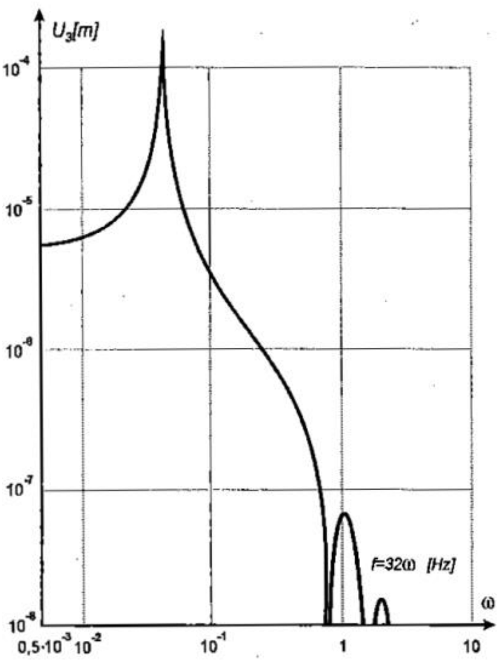

Fig. 6. Vertical displacement
Source: [Bril et al. 2016].

Analysing the results presented in Figures 5 and 6 it can be stated that:

- horizontal and angular vibrations of the structure are coupled, which is manifested by the occurrence of two coupled modes within the frequency range of 50-90 Hz,
- vertical vibrations are not coupled with the other motions of the structure. The natural frequency in the vertical direction is of the order of 0.03 Hz and it is below the frequency range under consideration,
- in the frequency range under consideration the mode corresponding to the vertical vibrations of the roadway is dominant,
- amplitudes of horizontal vibrations of the structure are one order of magnitude greater from the amplitude of vertical vibrations,
- graphs show that the structure modelled as a rigid body lying on the half-space has the properties of a low-pass filter,
- with the numerical data assumed in the example the largest amplitude is of the order of 10^{-3} [m] and it is related to the resonance of the roadway,
- amplitudes of rotational horizontal vibrations of the structure are of the order of 10^{5} [m], which results from the filtering properties of the structure.

Conclusion

A vehicle in motion (rail or road vehicle) causes the occurrence of dynamic phenomena of different natures, such as:

- interactions between respective subsystems, for example between a rail vehicle and a track, a track and foundation soil, foundation soil and a structure, and a road vehicle and a roadway,
- waves produced in the track and in its surroundings (soil),
- vibrations of elements of the systems: vehicle – track, soil – structures.

The model research presented in this paper on impacts exerted by means of transport on the environment is based on the concept of a 2-D system and modelling of the ground as an elastic half-space. The propagation of vibrations in the ground has been investigated, with respect to both their generation in the roadway – ground system and their impacts exerted on structures. The research on impacts exerted by means of transport on structures has made use of a model system comprising a vehicle interacting with a roadway modelled as a rigid mass band and the ground modelled as an elastic half-space.

The ground surrounding a track, a tunnel or a road, being a continuous medium, is in general non-homogenous and anisotropic. In the conducted research it has been assumed that the ground is isotropic and homogenous. Account has been taken of the complex nature of vibrations induced by means of transport (as para-seismic disturbances), among which the Rayleigh waves dominate. In the infinite elastic medium three types of waves may occur: longitudinal (dilatation) S waves, transverse (distortion) P waves and surface (Raleigh type) waves. The interference of three types of waves of different velocities results in the complex type of rumbling. Asymptotically, at the high values of the product ωx1, the components corresponding to the S and P waves decrease to zero and the surface state becomes steady in the form of Rayleigh waves.

This article presents the results of the model research and the calculation methods. The results of the model research have been confirmed by experiments. Article [Strzyzakowski 2007] provides the results of experiments consisting in taking measurements of spectral density functions of ground surface accelerations at different distances from the point source. The results of experiments are confirmed by the band-filtering properties of the ground surface with regard to the product ωx1. Article [Strzyzakowski 2007] includes also the results of the experiments consisting in measurements of the ground surface accelerations at selected distances taken perpendicularly to the track. With an increase in the distance from the source of forcing, spectral densities of ground acceleration spectra are characterised by low frequencies.

Model research on impacts exerted by means of transport on structures can be conducted at a lower cost than measurements and it can be used for the assessment of transport safety.

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Conflict of interests

The author declared no conflict of interests.

Author contributions

All authors contributed to the interpretation of results and writing of the paper. All authors read and approved the final manuscript.

Ethical statement

The research complies with all national and international ethical requirements.

ORCID

Joanna Bril – The author declared that she has no ORCID ID’s

Edward Rydygier – The author declared that he has no ORCID ID’s

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Biographical notes

Joanna Bril – Ph.D. in Sciences, Eng., Deputy Dean at the Faculty of Transport and Spatial Development and Manager of the Management Economics Department at the Higher School of Podkarpacie in Jasło (*Podkarpacka Szkoła Wyższa im. bł. ks. Władysława Findysza w Jaśle*), Board Member of the Polish Association of Transport Engineers and Technicians (*Stowarzyszenie Inżynierów i Techników Komunikacji RP*, SITK), SITK expert in eight disciplines. Main areas of interest include transport infrastructure, management, spatial planning, transport logistics and reverse logistics. Author of several dozen scientific papers, conference papers, books and course materials regarding transport, logistics and spatial planning. Experience of completing projects co-funded by the EU. Board Member of the Local Government Assembly of the Podkarpackie Province. Awarded with the Silver Cross of Merit for her contribution to the development of science and with the Medal of the Commission of National Education.

Edward Rydygier – Ph.D. in Sciences, M.Sc. in physics, holder of the professional title of European Physicist, researcher at McLeod Institute of Simulation Sciences at the Kazimierz Pulaski University of Technology and Humanities in Radom (*Uniwersytet Technologiczno-Humanistyczny w Radomiu*), chief specialist in the Municipal Office in Warsaw, member of the Polish Society for Computer Simulation (*Polskie Towarzystwo Symulacji Komputerowej*), the Polish Physical Society (*Polskie Towarzystwo Fizyczne*) and the Society in Tribute to Maria Skłodowska Curie (*Towarzystwo Marii Skłodowskiej Curie w Hołdzie*). Main areas of interest include modelling of engineering inverse problems, computer simulations in research on transport interface problems and reverse logistics. Author of over 100 scientific publications regarding transport, electrical engineering, logistics, information technology and physics, including the scientific contribution presenting the original numerical method for identifying field sources in "Lecture Notes in Pure and Applied Mathematics" (for 2001), world-renowned series published by Marcel Dekker Co. in N.J., USA. Holder of journalist licence and opinion journalist.

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