inter.noise 2010
noise and sustainability
13-16 June 2010 . Lisbon . Portugal
www.internoise2010.org

A ground-borne vibration assessment model for rail systems at-grade

J. Cardona[1]; J. Romeu[2]; R. Arcos[2]; A. Balastegui[2]

[1] AV Ingenieros. c/ Carles Riba, 8 bajos 3ª, 08173 St. Cugat del Vallès (Spain)
jcg@avingenieros.com

[2] Laboratory of Acoustics and Mechanical Engineering, LEAM. Technical University of Catalonia.
c/ Colom, 11, 08222 Terrassa (Spain)
jordi.romeu@leam.upc.edu

Abstract
Due to the increasing number and kilometres of new railways lines, either high speed railway lines or commuter lines, as well as the increasing in human sensitivity versus ground-borne vibration generated for this mean of transport, a sustained growth in complaints due to the annoyance caused by railway vibrations has been detected.

In order to predict the field vibrations caused by new railway lines in the project stage, which will be useful to design appropriate countermeasures, in the present work a ground-borne vibration model for rail systems at-grade developed by the authors is validated with experimental measurements in an existing commuter railway line. It checked that this model is a very useful tool to predict the vibration field that will be caused by a railway infrastructure in the planning stage of the project.

Keywords: Railway, vibrations, prediction model

1 Introduction

Either the new railway infrastructure constructions or their following modifications lead to the development of environmental impact assessment projects about their surroundings, specially taking into account the vibration consequences that the usual exploitation can cause.

Nowadays, a standard prediction model which permits this vibration impact determination does not exist yet, although it has been demanded by many Institutions, such as Union of International Railways, UIC [1]. For this reason, prediction studies are done according to several models developed by different authors using concepts and methodologies that may differ from each other, which actually entails an excessive variability and implies the need of much more data to validate all these models [2].

There are two main types of prediction models: the empiric ones, developed from the statistics of a great deal of experimental data [3] or from the combination of these results together with ground waves propagation theory [4] and theoretical models [5], which usually has a greatest application range but, in contrast, require more data that are often harder to obtain and, additionally, need heaviest calculations [4]. As a consequence, numerical options offer solutions to complex problems that are unfeasible for analytic methods [6].

Independently of the methodology used, authors frequently divide the problem in different regions: the generation region, another which is in charge of the propagation through the ground and, finally, the region that receives the vibrations inside the buildings [3,7], although other sub-regions can be found.

In this paper, a prediction model for the ground borne vibration propagation caused by at-grade railway traffic, based in a semi-analytical characterization of the propagation, is exposed. Therefore, movement equations in an infinite semi-space considered as homogeneous, isotropic and lineally elastic, are used and the superficial displacement equation depending on the source distance, caused by a vertical punctual excitation source placed in the ground surface, is determined [8,9]

2 At-grade railway vibrations

The excitation of the ground surface generates body primary waves, P, and shear waves, S, additionally to Rayleigh surface waves, R. The last ones are elliptically retrograde waves which propagate in normal direction to excitation source, not only in surface but also into the semi-space, with a high rate of attenuation in this last direction [8]

Just as exposed before, Rayleigh surface waves have lower geometric attenuation ratio than body waves and, therefore, they transport vibration energy to higher distances from the excitation source. According to this, it has been determined that vibration energy is distributed heterogeneously among these three waves, resulting in the following energy transportation distribution: 7% by compression waves, 26% by shear waves and 67% by Rayleigh surface waves, which corresponds to the highest quantity [10].

Due to the higher contribution to the energy transportation, as seen before, and the lower decaying rate, as other authors have been reported, Rayleigh surface waves are that considered in the development of the superficial ground borne vibration propagation model due to at-grade excitation sources.

The frequency range usually used in vibration impact assessment studies is 1-80 Hz, as national and international standards indicate [11,12]. Specifically in railway infrastructures where train pass-by takes place at-grade, the frequency range on interest depends on the type of running train and on the ground geology. Commercial trains' circulation on soft ground usually generates two frequency ranges with high vibration levels: 5-10 Hz and 30-50 Hz, taking into account that the softer the ground, the more important the first frequency range.

Therefore, and for grounds that are not too soft, the authors' experience indicates that the frequency range of interest can be 25-100 Hz, as shown in Figure 1, where different vibration spectra experimentally measured on the ground surface due to the traffic of different types of trains, are exposed.

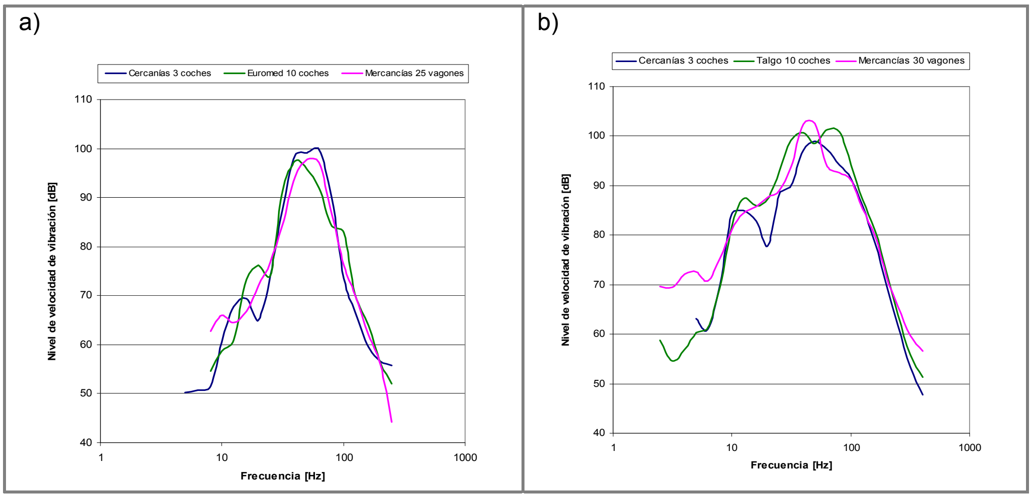

Figure 1. Vibration spectra measured on the ground surface: a) site 1, b) site 2.

In Figure 1, a) shows the vibration velocity spectra on the ground surface at 12 m far from the track centre (Rheda-2000 superstructure) due to the traffic of (——) 3 car commuter trains, (——) 10 car medium-speed trains (Euromed) and (——) 25 wagons freight trains, while b) shows the vibration velocity spectra on the ground surface at 8 m far from the track centre (ballasted track) due to the traffic of (——) 3 car commuter trains, (——) 10 car medium-speed trains (Talgo) and (——) 30 wagons freight trains.

3 Theoretical background

The prediction model is based on the concept that the train can be considered as a moving multi-punctual excitation source (due to the train velocity), where each axes of the train is considered as a point load that excites the sleepers of the superstructure as the train is running over them.

Therefore, each of the sleepers of the superstructure can be considered as a static punctual source of vibration that transmits the vibration to the ground as they are activated by the advance of the train axes. The dynamic behaviour of the multi-punctual source of vibration induces to a superficial wave generation whose wave front can be considered normal to the direction of propagation.

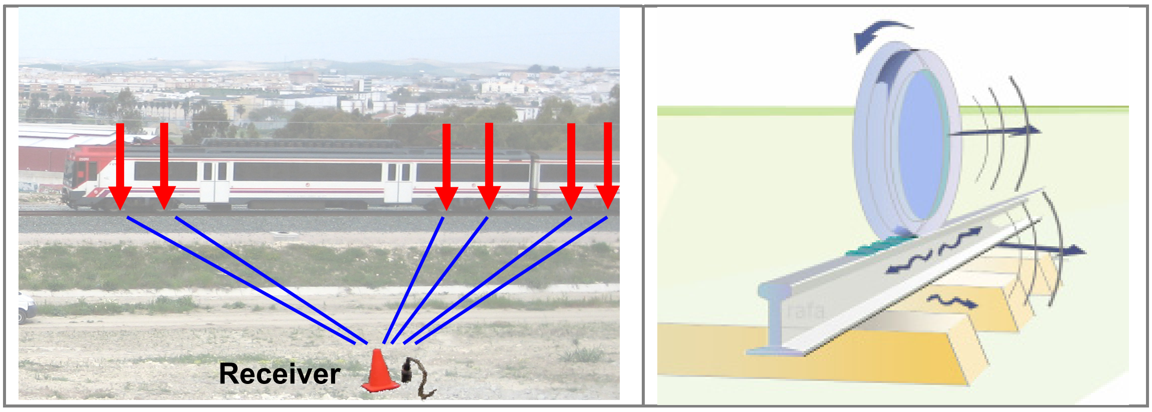

Figure 2. Outline of the multi-punctual source of vibration concept corresponding to a moving train.

The sleepers can be considered as punctual sources of vibration because in the low frequency range where we are working the characteristic wave length of the generated elastic waves is greater than the dimensions of the sleepers themselves [13], so that the calculation of the overall vibration field radiated by a moving train at-grade can be carried out through the superposition of each individual vibration field generated by each individual sleeper when they are activated by each of the axes of the train. Therefore, the inter-sleeper distance and the train velocity are parameters that should be taken into account [13].

3.1 Governing equations

The ground behaviour, which is considered as a semi-space, is described through the use of the Navier's elastodynamic equations. If we consider a body where the volumetric forces are negligible, the displacement governing equation is:

$$(\lambda + \mu)\cdot \nabla \cdot \nabla \cdot u + \mu \cdot \nabla^2 \cdot u = \rho \cdot \ddot{u} \qquad (1)$$

From this displacement expression it is possible to obtain the equations of the primary and secondary body waves (2) and (3) as well as their velocity expressions (4) and (5):

$$\frac{\partial^2 \varphi}{\partial t^2} = v_p^2 \cdot \nabla^2 \cdot \varphi \qquad (2) \qquad\qquad v_p = \left(\frac{\lambda + 2\mu}{\rho}\right)^{1/2} \qquad (4)$$

$$\frac{\partial^2 \psi}{\partial t^2} = v_s^2 \cdot \nabla^2 \cdot \psi \qquad (3) \qquad\qquad v_s = \left(\frac{\mu}{\rho}\right)^{1/2} \qquad (5)$$

From these new equations it is possible to obtain the integral solution of the superficial displacement for a punctual source placed on the ground surface. The horizontal displacement, ***w***, and the vertical displacement, ***q***, represented by the potentials φ and ψ are shown in the expressions (6) and (7):

- Horizontal displacement: $$q = \frac{\partial \varphi}{\partial r} + \frac{\partial^2 \psi}{\partial r \partial z} \quad (6)$$

- Vertical displacement: $$w = \frac{\partial \varphi}{\partial z} - \frac{\partial^2 \psi}{\partial r^2} - \frac{1}{r} \cdot \frac{\partial \psi}{\partial r} = \frac{\partial \varphi}{\partial z} + \frac{\partial^2 \psi}{\partial z^2} - \frac{1}{\beta^2} \cdot \frac{\partial^2 \psi}{\partial t^2} \quad (7)$$

Given that the potentials φ and ψ have to satisfy the previous wave equations, one can develop the expressions (6) and (7) in order to obtain the integral solution of the horizontal and vertical displacements, which evaluated by boundary and line integrals, produce the final expressions of the displacement. Thus, the time dependant equation of the vertical displacement can be written as a function of the distance, $\boldsymbol{r}$, the Lamé constant, , $\boldsymbol{\mu}$, the wave-numbers, $\boldsymbol{k}$, $\boldsymbol{k_\alpha}$ y $\boldsymbol{k_\beta}$, the force applied to the ground surface, $\boldsymbol{L}$, and the frequency, $\boldsymbol{\omega}$, where $K = f(k, k_\alpha, k_\beta)$.

$$w_0 = \frac{L\,K\,k}{\mu} \cdot \sqrt{\frac{1}{2\pi\,k\,r}} \cdot e^{i\left(\omega t - k r - \pi/4\right)} - \frac{L \cdot k_\alpha}{2\pi^2 \mu} \cdot \frac{\sqrt{2\pi}}{\left(k_\alpha r\right)^2} \cdot \frac{k_\alpha^2 \cdot k_\beta^2}{\left(k_\beta^2 - 2k_\alpha^2\right)^2} \cdot e^{i\left(\omega t - k_\alpha r - \frac{\pi}{4}\right)} - \frac{L \cdot k_\beta}{2\pi^2 \mu} \cdot \frac{4\sqrt{2\pi}}{\left(k_\beta r\right)^2} \cdot \left(1 - \frac{k_\alpha^2}{k_\beta^2}\right) \cdot e^{i\left(\omega t - k_\beta r - \frac{\pi}{4}\right)}$$

In this expression, the first term refers to the Rayleigh surface waves while the following two terms refers to the primary body waves, P, and secondary body wave, S. Given that the model only considers the Rayleigh surface waves, as discussed above, the vertical displacement expression, after introducing the material attenuation component, is as follows:

$$w_0 = \frac{L\,K\,k}{\mu} \cdot \sqrt{\frac{1}{2\pi\,k\,r}} \cdot e^{i\left(\omega t - k r - \pi/4\right)} \cdot e^{\alpha \cdot r} \quad (8)$$

3.2 The train as a vibration source

The train is modelled as a set a point loads (axes) exciting the sleepers of the superstructure as the train runs over them. Therefore, each sleeper of the superstructure can be considered as a static punctual source of vibration that transmits the vibration to the ground.

Thus, a numerical code that implements the vertical displacement equation (8) is developed and it allows to calculating the surface displacement field as a function of the distance to the excitation source. Figure 3.a shows the calculation of the time-dependant evolution of the surface displacement at a receiver placed on the ground surface due to a 6-car train pass-by. In this figure, dashed blue lines represent the contribution of each axes to the overall surface displacement and continuous red line represents the train pass-by. Figure 3.b shows the train pass-by displacement at different receivers placed at different distances de to excitation source.

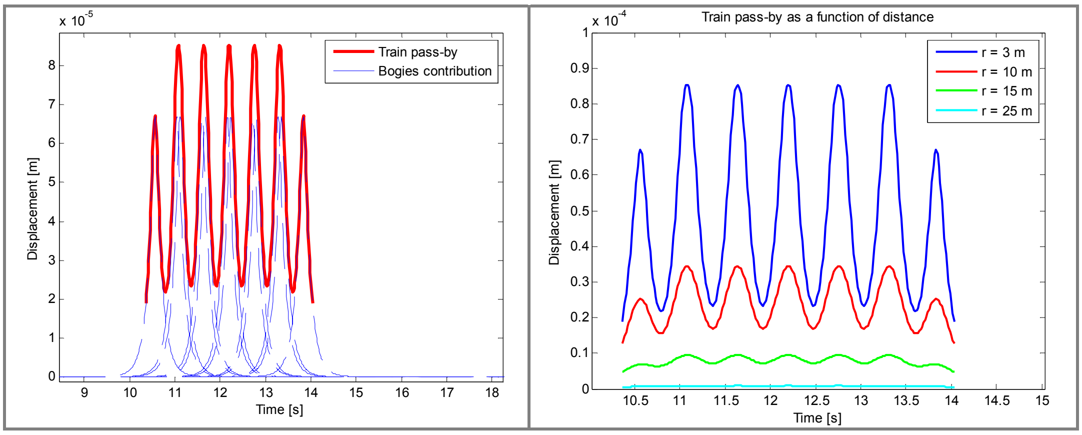

Figure 3. a) Axes contribution to the overall surface displacement (dashed blue line) due to a train pass-by (continuous red line), b) trains pass-by displacements at different distances to the source.

From the previous results, it is possible to determine the overall displacement level at each receiver as the integral of the time-dependant displacement amplitude along the time of train pass-by. The result of this integration is the evolution of the vibration level as a function of distance to the source, as is shown in Figure 4.

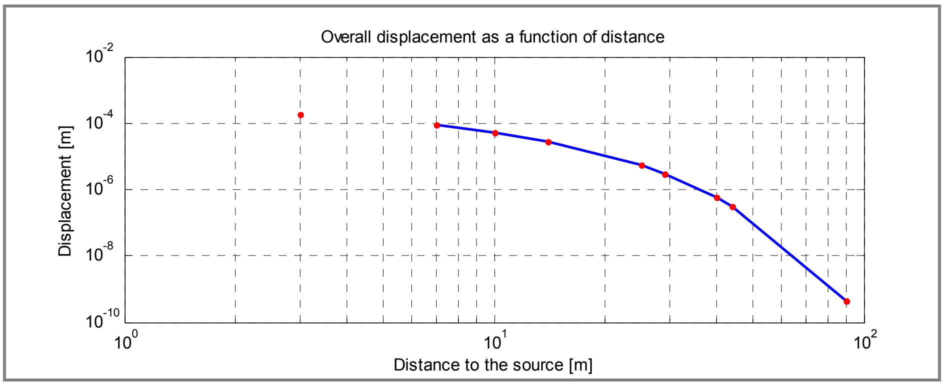

Figure 4. Ground borne vibration level as a function of the distance to the excitation source.

4 Validation

In order to validate the prediction model, some experimental measurements are carried out and the results are compared with those obtained by the prediction model. The experimental tests consist of the measurement of the ground borne vertical vibration level at different distances to a superficial railway track during the pass-by of different types of trains.

4.1 Validation site description

The test site is situated in the Spanish Mediterranean coast, near the city of Valencia, along the line between Barcelona and Valencia. This line is a double track with mono-block concrete sleepers spaced 0,6 m and SKL clip fasteners lying on ballast 50 cm height.

The ground is composed by materials from the quaternary with conglomerates, clay with pebbles and silt. The characteristic material attenuation coefficient, α, for these kind of grounds is in the range 0,05 $m^{-1} < \alpha <$ 0,15 m^{-1}. The experimental tests carried out at the test site using a drop-weight, suggest a value α = 0,08 m^{-1} to be used when the prediction is carried out using overall vibration values in the range 1-80 Hz.

The traffic of different kind of trains was measured at the test site, including commuter trains, regional trains and medium-speed trains. The velocity of the measured trains varies between 150 km/h for medium-speed trains and 110 km/h for commuter trains. Regional trains' average velocity during the test was 120 km/h.

Figure 5. Two types of the measured trains at the test site and a view of the drop-weight used to characterize the ground.

As can be seen in Figure 5, during the experimental test 6 simultaneous measurements points situated at distances 8, 13, 23, 38, 53 and 83 m far from the track centre, were arranged.

4.2 Experimental results and validation

Experimental results show the overall vertical vibration magnitude between 1-80 Hz on the ground surface as a function of the distance to the railway track, for the different types of train under study and for the different pass-by measured.

Train pass-by generates transient signals, so that we work with the energy spectral density, ESD, because it is the best function to characterize the transient phenomenon.

Figure 6 shows overall vibration values measured on the ground surface at different distances to the railway track during the traffic of a) 7 medium-speed trains, b) 17 commuter trains and c) 4 regional trains. Also, Figure 6 shows the simulated overall vibration values in continuous red line superimposed over the experimental results. The simulated results are obtained for the following traffic conditions:

a) 10 cars medium-speed train running at 150 km/h
b) 3 cars commuter train running at 110 km/h
c) 3 cars regional train running at 120 km/h

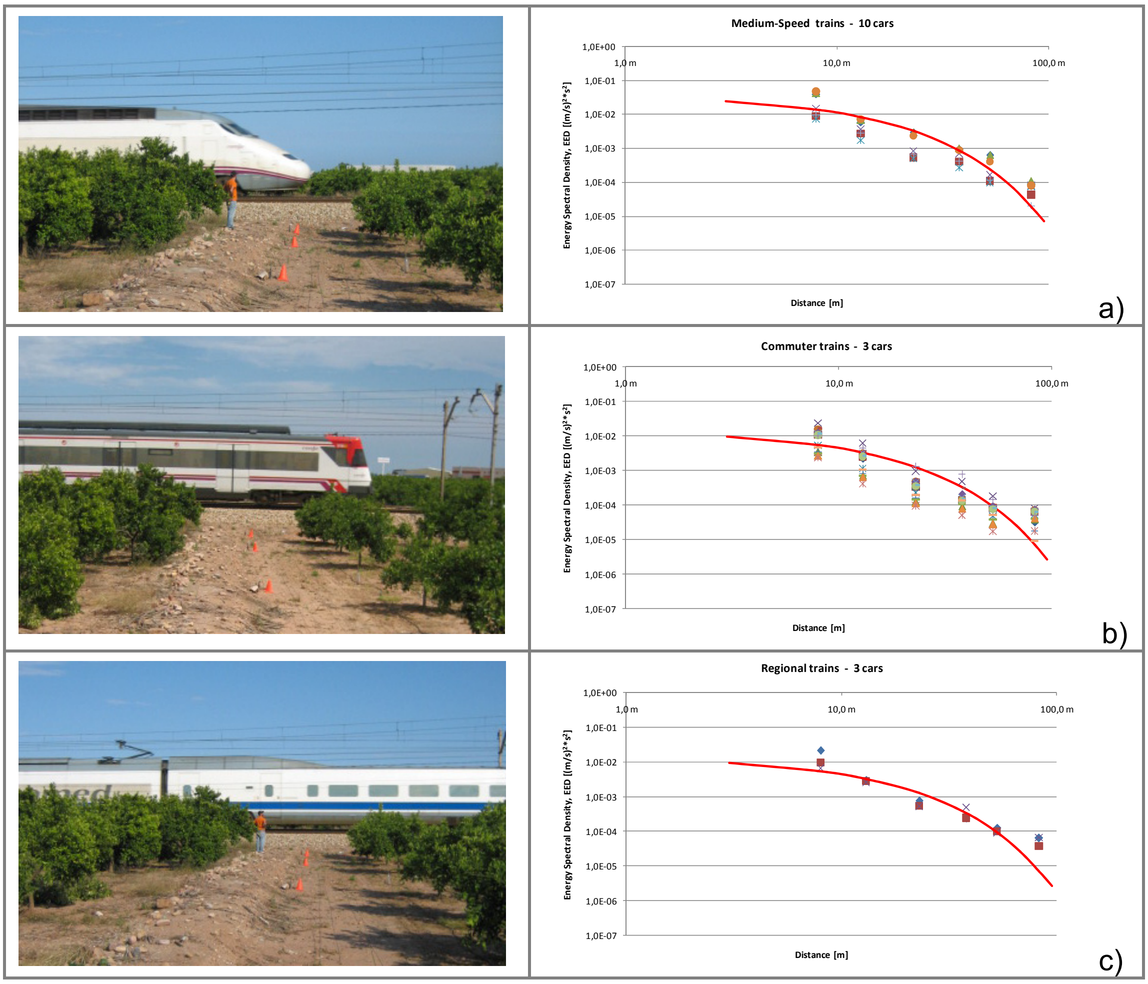

Figure 6. Experimental measurement results and simulated results, in continuous red line.

As can be seen in figure above, the prediction model is capable to describe with a high degree of reliability the propagation law of the vibration on the ground surface caused by railways at-grade. Only at large distances from the source some minimum deviation of the simulated data with respect to experimentally measured values are observed.

5 Conclusions

In the present paper, a prediction model for the ground borne vibration propagation caused by at-grade railway traffic, based in a semi-analytical characterization of the propagation, is exposed.

The train as excitation source is modelled as a moving multi-punctual load running over the sleepers which are considered as static point excitation sources as they are activated by the advance of the train bogies (the moving point loads).

Therefore, movement equations in an infinite semi-space considered as homogeneous, isotropic and lineally elastic, are used and the superficial displacement equation depending on the source distance, caused by a vertical punctual excitation source placed in the ground surface, is determined. The material attenuation component is added to this expression in order to take into account the ground geology where the vibration propagation takes place. A numerical code that implements the vertical displacement equation allows to calculating the surface displacement field as a function of the distance to the excitation source.

The propagation prediction model is validated with experimental measurements during the circulation of different types of trains at a test site, with satisfactory results that shows a good agreement between measured and simulated data.

Acknowledgments

Acknowledgments to the Spanish Ministerio de Fomento for the grant that has been made possible to reach to these results and to all the members of the Laboratory of Acoustics and Mechanical Engineering, LEAM, for their support in the experimental tests and post-processing data.

References

[1] Hemsworth, B. *Reducing ground borne vibrations: State of the art study*. Journal of Sound and Vibration, 231(3), 2000, pp.703-709.
[2] Degrande, G., Schillemans, L. *Free field vibrations during the passage of a Thalis high-speed train at variable speed*. Journal of Sound and Vibration, 247(1), 2001, pp.131-144.
[3] Hanson, C.E., Towers, D.A., Meister, L.D. *Transit noise and vibration impact assessment.* U.S. Department of Transportation, Federal Transit Administration. 2006.
[4] Jones, C.J.C.; Block J.R. *Prediction of ground vibration from freight trains.* Journal of Sound and Vibration, 193(1), 1996, pp. 205-213.
[5] Lu, F., Lin, J.H., Kennedy, D., Williams, F.W. *An algorithm to study non-stationary random vibrations of vehicle-bridge systems*. Computers and Structures, 87, 2009, pp. 177-185.
[6] Yang, Y.B., Hung, H.H., Chang, D.W. *Train-induced wave propagation in layered soils using finite/infinite element simulation.* Soil Dynamics and Earthquake Engineering. 23, 2003, pp. 263-278.

[7] Bahrekazemi, M. *Train-Induced ground vibration and its prediction*. PhD Thesis, Division of Soil and Rock Mechanics, Department of Civil and Architectural Engineering, Royal Institute of Technology, Stockholm 2004.

[8] Bedford, A., Drumheller, D.S.. *Introduction to elastic wave propagation*. John Wiley & Sons. 1996.

[9] Ewing, W. M., Jardetzky, W. S., Press, F. *Elastic waves in layered media*. MacGraw-Hill. 1957.

[10] Miller, G.F., Pursey, H. *On the partition pf energy between elastic waves in a semi-infinite solid*. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, 233(1192), pp. 55-69.

[11] International Organization for Standardization. ISO 2631-2: Mechanical vibration – Evaluation of human exposure to whole-body vibration. Part 2: Vibration in buildings (1 Hz to 80 Hz). 2003.

[12] Deutsches Institut für Normung. DIN 4150-2. Structural vibration. Part 2: Human exposure to vibration in buildings. 1999.

[13] Krylov, V.V. *Generation of ground vibrations by superfast trains.* Applied Acoustics, 44, 1995, pp. 149-164.