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Influence of railway induced vibrations on structures and humans in urban areas

Authors:

Nikola Naumovski, PhD. ME
Institute of Earthquake Engineering & Engineering Seismology, Skopje, North Macedonia
nikolan@iziis.ukim.edu.mk

Prof. **Viktor Hristovski**, PhD. CE
Institute of Earthquake Engineering & Engineering Seismology, Skopje, North Macedonia
viktor@iziis.ukim.edu.mk
Corresponding author

Prof. **Lidija Krstevska**, PhD. CE
Institute of Earthquake Engineering & Engineering Seismology, Skopje, North Macedonia
lidija@iziis.ukim.edu.mk

Research Paper - Subject review

Nikola Naumovski, Viktor Hristovski, Lidija Krstevska

Influence of railway induced vibrations on structures and humans in urban areas

Railway traffic is a significant source of vibration that can affect the quality of life of people living near busy railways. This study proposes an integrated methodology for analysing the impact of vibrations from railway traffic on people and nearby buildings and measures for reducing their effects. The research includes both in-situ measurements and numerical modelling of railway traffic-induced vibrations. The proposed integrated methodological approach is implemented on a section of the active Kumanovo–Deljadrovci railway line in North Macedonia. The knowledge gained through this research is intended to provide a good basis for defining national standards for this increasingly relevant issue.

Key words:
railway vibrations, in-situ vibration measurement, finite element method, attenuation curve

Pregledni rad

Nikola Naumovski, Viktor Hristovski, Lidija Krstevska

Utjecaj vibracija uzrokovanih željezničkim prometom na građevine i ljude u urbanim područjima

Željeznički promet značajan je izvor vibracija koje mogu utjecati na kvalitetu života ljudi koji žive u blizini prometnih željezničkih pruga. U ovom je istraživanju predložena integrirana metodologija za analizu utjecaja vibracija uzrokovanih željezničkim prometom na ljude i okolne zgrade te mjere za smanjenje njihovih učinaka. Istraživanje uključuje mjerenja in situ i numeričko modeliranje vibracija izazvanih željezničkim prometom. Predloženi integrirani metodološki pristup provodi se na dijelu aktivne željezničke pruge Kumanovo–Deljadrovci u Sjevernoj Makedoniji. Saznanja stečena ovim istraživanjem trebala bi pružiti dobru osnovu za definiranje nacionalnih normi za ovo sve relevantnije pitanje.

Ključne riječi:
vibracije uzrokovane željezničkim prometom, mjerenje vibracija in situ, metoda konačnih elemenata, krivulja prigušenja

1. Introduction

This study presents an updated and improved version of the paper originally published in the 1CroCEE conference (1st Croatian Conference on Earthquake Engineering), [1].

Railway traffic is a significant source of vibrations that affects the quality of life of people living near railway lines with frequent traffic. Vibrations caused by railway lines were first observed and determined to be a problem during the construction of underground traffic lines. However, lately, vibrations caused by surface railway lines have increasingly attracted attention. Vibrations transmitted through the soil are usually accompanied by structural noise transmitted through the air, which may also pose a big problem. The manifestation of these two phenomena (vibrations and structural noise) depends mainly on the type of traffic, railway surface condition, fastening system, resilient elements in the track structure and soil type.

Although vibrations caused by passing trains are not conceived as the major reason for inflicting structural damage on neighbouring buildings, additional damage caused by the vibrations have been observed in some old masonry structures [2, 3]. Moreover, structures damaged by earthquake may suffer additional damage caused by the vibrations with the latest example of such a case being the earthquake in Zagreb, which occurred in March 2020 [4-9]. On the other hand, vibrations are often the reason for continuous anxiety and discomfort in the occupants of buildings located near railway lines. However, the effect of vibrations on the comfort of the people and their anxiety is a very complex problem that cannot be solely treated by considering observed vibrations levels but should also include noise caused by passing trains and transmitted through the air [10]. Moreover, we have witnessed the increasing topicality of the problem. The ecological concerns are probably the reason behind the increasing attention of the society, particularly engineers and architects dealing with urban planning, to the problem of vibrations caused by trains and their effect on the comfort of the people, and functioning of sensitive equipment installed in structures exposed to vibrations.

Currently in Republic of North Macedonia, there are no national guidelines or standards related to vibrations from various sources and their effect on occupied structures. There are a number of national standards in Europe [11-13], the USA [14], Australia [15], Japan [16]), etc.; however, the acceptable (allowed) level of disturbance varies. Not all countries have specific limitations for vibrations caused by railway lines, and the European legislation on railway vibrations is still under development; albeit, it is in the later stage of development. At the EU level, the Directive (EU) 2016/797 of the European Parliament and Council, dated 11 May 2016, related to the interoperability of the railway system within the framework of the European Community [17]. Annex III (Basic Requirements), paragraph 1.4.5 (Protection of Human Environment), states that operation of the railway system and its maintenance must not give rise to an inadmissible level of ground vibrations in areas close to the infrastructure.

The aim of this study is to acquire knowledge on the nature of railway vibrations, their propagation and effect on people and structures for the purpose of developing an integrated approach to analyse the effect of vibrations and take measures to eliminate or mitigate the effects thereof. The proposed integrated approach is implemented on a section of Kumanovo–Deljadrovci railway line in North Macedonia. This can be used to develop a long-term strategy for the analysis of vibrations resulting from railway traffic for the reconstruction of existing and construction of new railway lines.

Notably, the effects of vibrations on the human body represents an almost unexplored field of study. Early studies and systematic observations of the effects of vibrations on people in the sense of clinical, medical, and psychological research, including comfort, date back to the nineteenth century. In the twentieth century, scientific literature on this topic increased considerably with the increase in development and expansion of industry, transport and urbanization. One of the first and most popular systematic studies on this topic by Goldman and von Gierke [18] dates back to the beginning of the 1960s. In the seventies, several important studies on the effect of vibration on human were published by Griffin [19]. Great advances have been made over the last fifty years such that a number of studies, such as the state-of-the-art report presented in [21] and historical review in [20] can be considered as standards in this field.

2. Integrated methodology for estimating vibration level

The final goal of the presented methodology for analysing the effect of vibrations owing to railway traffic on people and structures is to propose corresponding measures for mitigating their effect. In this way, a long-term development strategy can be implemented for the analysis of vibrations owing to railway traffic in the reconstruction of existing and construction of new railway lines. The research has been realized in a number of phases: (1) exploration of existing experience and knowledge, literature, and standards regarding railway traffic vibrations; (2) in-situ measurement of vibrations at selected critical points at locations in urban area for a selected section of the railway line to obtain the attenuation curves necessary for an assessment of the effect of vibrations; (3) definition and verification of the numerical models based on the finite element method (FEM) to verify the attenuation curves obtained from in-situ measurements; (4) analysis of the data obtained and assessment of the effects (i.e. the effect of the vibration level on structures and people using the corresponding existing standards); (5) defining the mitigation measures for the level of vibration caused by railway traffic. The proposed integrated methodological approach for defining and analysing the vibrations and their effect has been implemented on a specific section of the Kumanovo–Deljadrovci railway line. The knowledge obtained in this research can provide a good basis for defining the national standards of North Macedonia for the problems associated with railway vibrations, which are increasingly gaining importance.

2.1. In-situ measurements

The proposed methodology includes site investigations and numerical modelling and analyses. The methodology was implemented in the Kumanovo–Deljadrovci railway section within the framework of the project for the geophysical investigation of soil properties and measurement of vibrations caused by passing trains [22]. The site investigation included the following steps:

- Identification of critical zones (hotspots) and field observation of all buildings near the railway line.
- Geophysical measurements for selected profiles of the critical zones using the "hammer blow" method and defining the geological profiles with the properties of soil layers [22].
- Measurement of vibration intensity in terms of velocity owing to passing trains for the selected profile and acceleration using accelerometers [23].
- Construction of attenuation curves based on the measured velocities and accelerations to make a prognosis regarding the level of vibration in structures situated at the hotspots.
- Evaluation of the necessary measures for the reduction of vibrations.

The measurements were conducted for the profile "RP-3 Romanovce" [23] for the Kumanovo–Deljadrovci railway section. To perform the measurements, equipment with an acquisition system consisting of seismic accelerometers that records vibrations was used. A PCB Piezotronics device, model 393B12, manufactured by National Instruments, with a sensitivity of 10,000 mV and range up to 4.9 m/s^2 (i.e. 0.5 g), having NI 9234 cards, was used.

Two case studies were investigated, cases with or without a nearby structure (a small house 11 m away from the railway track). Five types of tests were conducted, namely, ambient vibration and hammer blow tests, and the passing of a passenger train, freight train, and locomotive. All measurements were performed at five points; for the study with no house, the five points were on the soil surface, whereas for the study with a nearby house, three points were located in the structure and two on the soil surface. The data analysis were performed according to the Polish PN-88/B-02171 standard [13], which is based on the ISO 2631-1 [24] and ISO 2631-2 [25] standards. Figure 1 shows the Fourier spectrum obtained from the acceleration measurements of the furthest point (no. 5) at a distance of 60 m from the railway track using the profile RP 3 (Figures 2 and 6 show the measurement points and FEM model, respectively). This case was without a nearby structure with a freight train passing by. These results were selected as representative ones for comparison with the natural vibration frequencies of the soil deposit obtained through numerical analysis (presented in the next chapter) because the influence of the excitation at point no. 5 had the least expression.

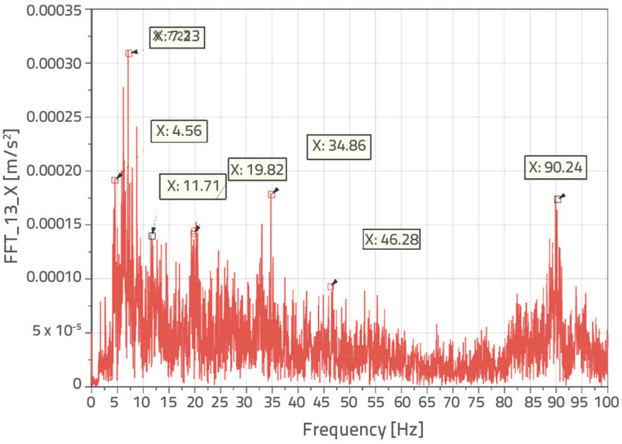

Figure 1. **Fourier spectrum for the selected soil profile RP-3 Romanovce, x-direction**

Figure 2. **Measurement points on the profile RP-3 Romanovce: in plan (top photo) and view (bottom photo)**

The bar chart in Figure 3 shows the measured level of vibrations in the nearby house. The vibration frequencies and intensities were compared to those provided in the PN-88/B-02171 standard [13] (diagrams for n = 1, 1.4, and 4, where n is a parameter that depends on the number of repetitions of events). The dashed and solid lines are related to the horizontal and vertical direction of human perception, respectively.

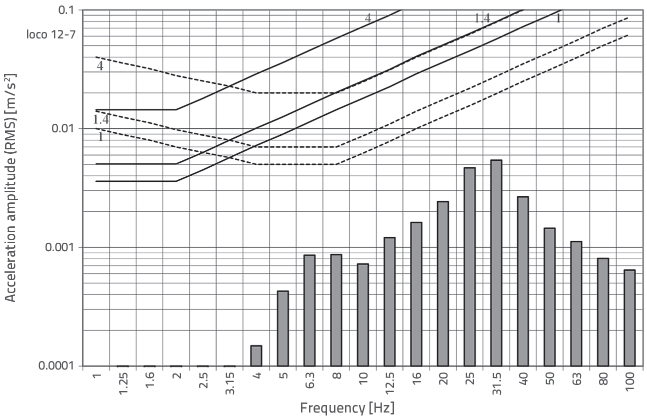

Figure 3. Bar chart of the measured level of vibrations in a nearby house compared to the human threshold perception levels (diagrams above the bars indicate different values of the parameter n = 1, 1.4, and 4) based on the PN-88/B-02171 standard [13]

2.2. Construction of seismic–geological profiles using geophysical tests

The hammer blow test was used to determine the wave-propagation properties of the soil media for the selected hotspots [22]. The purpose of this test is to generate a vibrational impulse that travels from a source (point of impact) to a receiver (object) in a similar way to that of train-induced vibrations. The installed sensors (meters) recorded the values via a multi-channel acquisition system. The transfer function (attenuation curve) was obtained for each selected profile based on the ground response to a hammer blow measured by 12 geophones placed 5 m apart in the transverse profile with a length of 60 m (Figures 2 and 6). The values were also obtained by placing the accelerometers at five points, in three directions, at 10 min intervals (note that the first point was located at 5 m away from the railway line). The seismic-geological structure of the measured profile was compiled using geophones. By calculating the obtained velocity in acceleration, the accelerations at all 12 measuring points (geophones) were obtained, and thus the attenuation curve of the profile was obtained.

The hammer blow geophysical test was used to estimate the propagation velocities of the seismic waves (longitudinal velocity V_p and transversal velocity V_s) for all seven profiles along the Kumanovo–Deljadrovci railway section. Figure 4 shows the seismic–geological distribution of the soil layers for the profile "RP-3 Romanovce", and the velocities obtained: V_p = 390 m/s and V_s = 170 m/s for layer 1 (0–2.0 m depth); V_p = 870 m/s and V_s = 390 m/s for layer 2 (2.0–11.0 m depth); and V_p = 2200 m/s and V_s = 850 m/s for layer 3 (11.0–20.0 m depth) (Table 1). These velocities were used to identify the properties of the soil layers used in the numerical FEM modelling and analysis. Layer no. 2, denoted as "el-dl", consisted mostly of eluvial material combined with deluvial dusty clay deposits, whereas layer no. 3, denoted as "Pl", was mainly composed of sand, clay, and sandstones.

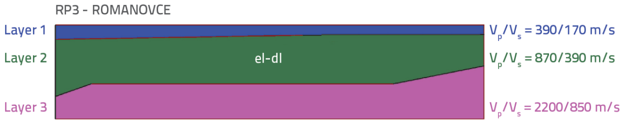

Figure 4. Geophysical test results for the selected soil profile RP-3 Romanovce

2.3. Numerical modelling and analysis

From a computational point of view, mechanical vibrations induced in the soil because of moving trains represent a complex dynamic problem. For modelling of the entire system (source of vibration, soil, and structures), the physics of vibration propagation and conditions affecting the propagation must necessarily be known. According to Yang and Hung [26], four main phases of vibration transmission through the soil medium from the source (i.e. railway line to exposed building structures) are differentiated. The first phase is the generation of vibrations; the second phase involves the transmission of vibrations through the soil medium; the third phase refers to the receipt of vibrations by the nearby building structures; and the fourth phase refers to the reduction in vibrations as a result of an appropriately designed foundation structure or barriers installed for protection against vibrations, etc. The integral problem involving all four phases can be solved

Table 1. Properties of the soil layers

Layers / Parameters	Layer 1: H = 0.0 – 2.0 m	Layer 2: H = 2.0 – 11.0 m	Layer 3: H = 11.0 – 20.0 m
V_p [m/s]	390	870	2200
V_p [m/s]	170	390	850
r [t/m³]	1.0	1.1	1.2
h [m]	2.0	9.0	9.0
m	0.383	0.374	0.412
E [kPa]	79921	459853	2448867

through various approaches that can be used individually or combinedly. The following approaches have been established so far: the analytical approach, field (in situ) measurements, models with empirical prediction (by establishment of attenuation curves) and numerical modelling and simulation. Numerous authors have proposed different analytical approaches and methods [27]. These approaches are defined by close analytical relationships and solutions that depend on parameters, such as train speed, distance, soil properties, etc. However, the approach involving in-situ vibration level measurements while different types of railway vehicles are in motion, enables the study of their effect on nearby structures and occupants. In addition, these measurements provide data and attenuation curves that make it possible to obtain the minimum distance of structures from the railway where the level of vibration is below that is allowed by the applicable standards. Although these measurements (similar to those discussed in section 2.1) require intensive activity and are often too costly if obtained in combination with the establishment of attenuation curves, these may provide an important factor for the quantification of the vibration level.

Apart from in-situ measurements, numerical modelling was used in this study for several reasons. First, it was developed to verify the in-situ measurements, and second, to calibrate the numerical model. The proposed numerical model can then be a useful tool for the numerical prediction of vibration levels in an affected structure. The verification of the FEM model and a discussion of the comparison between the results of the measured natural frequencies of the soil deposit and those obtained numerically are presented in this study. Moreover, the results of the dynamic analyses for the calculation of the time–history of the vibrations using the same numerical model is discussed. As previously mentioned, the site investigations and analyses were conducted for a profile section on the Kumanovo–Deljadrovci railway section.

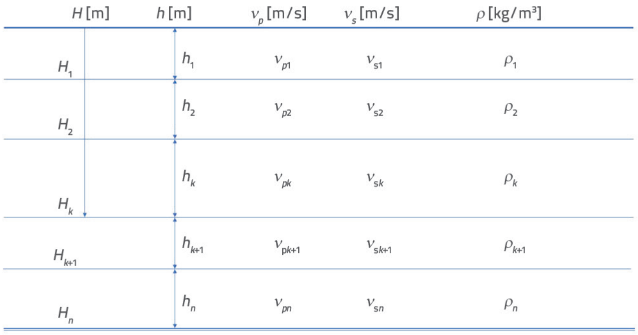

Figure 5. Generalized geotechnical model (GTM) with basic parameters for all soil layers

The dynamic properties of the soil medium play a key role in the transmission of vibrations to nearby structures. However, they are dependent on many factors, including the geological composition, number of layers, spatial distribution, depth, H_i, and thickness, h_i, of the layer and the material properties of the layer, such as unit density, ρ_i, Young's modulus of elasticity, E_i, shear modulus, G_i, Poisson's ratio, n_i, angle of internal friction and material cohesion. Figure 5 shows a generalized geotechnical model [28] with basic parameters for all soil layers. The velocities of propagation of longitudinal seismic wave, V_p, and transversal seismic wave, V_s, are generally expressed as functions of the material properties of the actual soil layer (i.e. Young's modulus of elasticity, E, shear modulus, G, density, ρ and Poisson's ratio ν) as follows:

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

$$V_s = \sqrt{\frac{G}{\rho}} \tag{2}$$

However, if the velocities of the transversal seismic waves for all soil layers are known from geophysical measurements, the predominant period of vibration, T_0, for the soil profile can be calculated using the following well-known equations [28]:

$$T_0 = \frac{4H}{\overline{V_s}} \tag{3}$$

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$$H = \sum_{i=1}^{n} h_i \tag{4}$$

$$\overline{V_s} = \frac{\sum_{i=1}^{n} V_{si} h_i}{\sum_{i=1}^{n} h_i} \tag{5}$$

The period of vibrations, T_m, for the higher mode m can be obtained using the following equation:

$$T_m = \frac{4H}{(2m-1)\overline{V_s}} \tag{6}$$

The numerical models usually used in the analysis of soil and rock continuums with and without consideration of discontinuities are [29]:

- Models of a continuum using the Finite Difference Method (FDM), FEM, and Boundary Elements Method (BEM).
- Models of a discontinuum using the Discrete Element Method (DEM), and Discrete Fracture Network method (DFN).
- Hybrid models of continuum/discontinuum using the hybrid FEM/BEM, hybrid DEM/DEM, and hybrid FEM/DEM methods.

The analyses of vibrations caused by railway traffic and their propagation in this study were conducted with two-dimensional (2D) and three-dimensional (3D) models using FEM. For 2D models, the plain-strain case per unit length in the direction normal to the considered half-space needs to considered. These 2D models are adequate if the source of vibration is located along the length normal to the considered half-space (as for the motion of passenger and freight trains); however, these models can also be used for point sources of vibration (e.g., hammer blows). In contrast, although 3D models eliminate possible problems in modelling of sources of vibration, these require greater memory and time-consuming computations and more refined discretization, regardless of which numerical method is used.

The main problem that arises in modelling the half-space with FEM is how to define the considered domain of the source and vibration transmissions (i.e. defining the boundary conditions). In addition to the methods applied in the previous investigations, there are several approaches to solve this problem using only FEM:

- Modelling of an additional domain of the half-space in the horizontal direction, within a radius of 3–5 depths of deposit, measured down to bedrock.
- Modelling of corresponding springs at the ends of the encompassed domain to stimulate the effect of the surrounding media.
- Use infinite elements at the ends of the encompassed domain.

The first two approaches were used in this research. The first approach was used for the 2D model developed using finite elements where additional domains were added to the left and right in the horizontal direction, within a radius of three depths of the soil deposit. The boundary conditions per translational degrees of freedom along lengths of the boundary were prescribed zero displacements. The second approach involving placement of springs on the boundary surfaces of the domain was used in the development of the 3D model with finite elements. Both models are discussed in more detail further in the text. To execute the numerical modelling and dynamic analysis of the considered domain under the effect of vibrations, the *E*, *G*, *n* and *r* parameters for all soil layers had to be defined. The following equation between the shear modulus, *G* and Young's modulus of elasticity, *E*, from the theory of elasticity was used:

$$G = \frac{E}{2(1+2\nu)} \tag{7}$$

The Poisson's coefficient, *n*, and Young's modulus of elasticity, *E* can be obtained from the system of Eqs. (1), (2), and (7), as follows:

$$\mu = \frac{2V_s^2 - V_p^2}{2\left(V_s^2 - V_p^2\right)} \tag{8}$$

$$E = 2V_s^2 \rho (1+\nu) \tag{9}$$

The density, ρ, can be obtained in the laboratory based on in-situ measurements of soil specimens. Because this type of measurement was not conducted in our investigation, the density of the soil layers was adopted based on empirical tables that include the classification of soils. In accordance with the velocities measured from the geophysical investigations for the profile "RP-3 Romanovce", using Eqs. (7), (8), and (9), the necessary elastic-mechanical characteristics of the soil layers were computed for the analysis using finite elements, as listed in Table 1.

The 2D and 3D FEM models were generated with this initial estimation of the elastic-mechanical characteristics of the soil layers computed using known velocities (previously obtained through special geophysical measurements), and the position and orientation of the layers in the considered profile "RP-3 Romanovce" (Figure 4). The 3D model (Figure 6) consists of 3D SOLID isoparametric elements with 20 nodes for modelling the soil half-space, integration scheme 3 x 3 x 3 = 27 Gauss (integration) points and 3D point SPRING elements (springs) with assigned values of stiffness along the three global translational degrees of freedom X, Y, Z at all nodes of the four vertical boundary surfaces within the surrounding soil medium. The lowest horizontal surface was modelled by preventing displacements along the three global degrees of freedom X, Y, Z. This served as a calibration model for the layer characteristics and verification of the results obtained for the natural vibrations of the soil deposit for the considered profile "RP-3 Romanovce". The 2D model (Figure 7) consists of a mesh of 2D isoparametric rectangular elements with 8 nodes and integration scheme 3 x3 = 9 Gauss (integration) points.

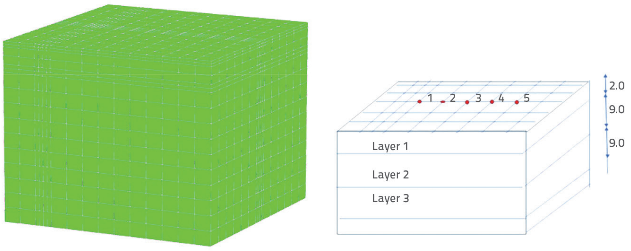

Figure 6. 3D finite element model of the analysed soil deposit (left) with indicated measuring points (right). Point 1 is the point that is the closest to the railway line (at a distance of 5 m), whereas the distance between the measuring points is 10 m

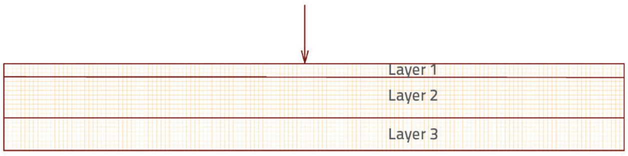

Figure 7. 2D finite element model of the analysed soil deposit

This model encompassed the source of vibrations and five control (measuring) points by adding additional finite element meshes on the left and right sides, within a length of 3 times the deposit depth (approximately 20 m). All three boundary lines (two vertical and lowest horizontal) were modelled with prevented displacements along the two global axes H, Y. This model resulted in an complete dynamic analysis and provided the attenuation characteristics of the media.

The stiffness of the springs in the 3D model and final soil properties of both the 2D and 3D models were calibrated in such a way that the obtained frequencies (i.e. natural periods of vibrations of the deposit) correlated logically with the results obtained from the in-

Table 2. Comparison of resonant frequencies in [Hz]

Mode	2D GTM	3D FEM	Test
1	7.188	7.427 (Y)	7.23 (X)
2	21.563	19.25 (X)	19.82 (X)
3	35.938		34.86 (X)
4	50.313		46.28 (X)
5	64.688		
6	79.063		82.45 (Y)
7	93.438		95.01 (Y)

situ measurements and numerical predictions conducted via the generalized geotechnical model (GTM).

The natural frequencies of vibrations of the considered deposit using the 2D GTM (i.e. Eqs. (3)-(6)) and using the 3D FEM model are listed in Table 2 comparatively. In addition, Table 2 compares the resonant vibration frequencies obtained through the measurements, thus taking into account the Fourier spectrum shown in Figure 1. Moreover, Table 2 specifies the direction (X or Y) referred to for obtaining the vibration frequencies. The results evidently show the validity and practicality of the 2D GTM despite its obvious flaws. However, more importantly, the finite element models are verified which further enables dynamic analysis (i.e. simulation of propagation of vibrations through the soil media).

The results of the dynamic analysis are presented for the case of using hammer blow as the source of vibration, obtained from the 2D FEM. A dynamic analysis was performed using the step-by-step Wilson θ method and adopting $\theta = 1.37$. The diagrams for attenuation of amplitudes of peak accelerations as a function of distance are shown in Figures 8 and 9.

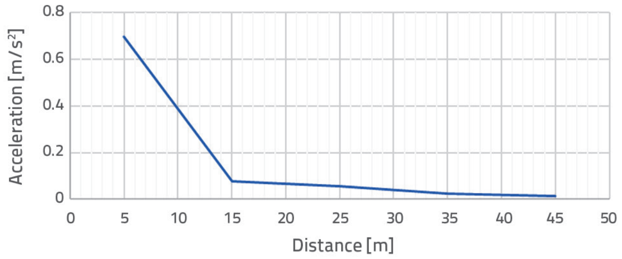

Figure 8. Attenuation curve obtained in the z direction due to dynamic excitation from a hammer blow; the numerical analysis used the FEM

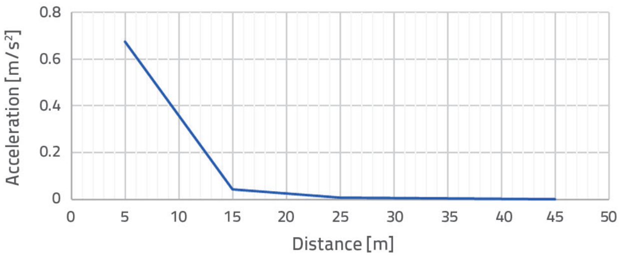

Figure 9. Attenuation curve obtained in the z direction due to dynamic excitation from a hammer blow; results from in-situ measurements

A comparison has been made between the attenuation curves obtained in the vertical, Z-direction (i.e. between the results obtained numerically using FEM (Figure 8) and those measured in-situ (Figure 9)). Similar comparisons were obtained for the horizontal directions X and Y [23].

Based on the comparative attenuation curves and considering their logical correlation, it is obvious that numerical modelling and prediction of the attenuation of the vibration intensity using FEM should be a constituent part of the procedure for the evaluation of the effect of vibrations from railway traffic on structures and people in the surrounding area, and the design of possible mitigation solutions. Certainly, the results from the numerical analyses will be more precise if the input parameters, i.e. the elastic-mechanical characteristics of the soil materials through which the waves propagate, geometrical characteristics, and orientations in space are more precisely defined. This illustrates that the classical FEM, based on the theory of elasticity, can be useful in creating attenuation curves, i.e. vibration effect curves with a distance from the source. The numerical analyses in this study was completed using the software package FELISA/3M, developed at UKIM-IZIIS, Skopje [30].

3. Measures for mitigating vibrations

According to [31], mitigation of vibration intensity can be achieved by:

- an increase in elasticity of the railway track structure
- the elimination of surface discontinuities through which the vibrations propagate
- regular maintenance of the surface of motion along the rails
- regular maintenance (re-profiling) of vehicles
- selection of a corresponding type of a railway vehicle
- reduction of the speed of railway vehicles.

A previous study [22] pointed out that the most efficient way to control vibrations is to control the source of the vibration. Therefore, for railway line formation, the main measures undertaken could be the following:

- stabilisation of the soil below the embankment
- placement of a slab or ballast bed
- placement of elastic under-sleeper pads (USP)
- placement of a base course below the ballast
- placement of barriers along the alignment.

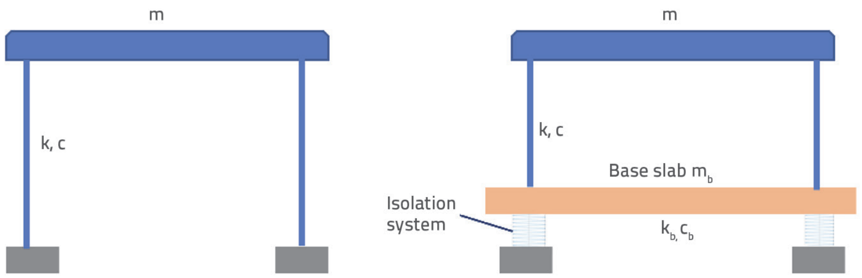

Figure 10. Un-isolated (left) and isolated (right) systems

3.1. Proposed mitigation measures for vibrations along the Kumanovo–Deljadrovci Railway Line

The application of USP was imposed as the most appropriate solution for a maximum train speed of 120 km/h along the Kumanovo–Deljadrovci railway line section, taking into account that only the replacement of timber sleepers by concrete ones is planned without any changes to the formation (ballast).

Practically, the solution represents a type of base isolation that can also be used to protect building structures near the railway line. The methodology of applying a base isolation by placing rubber pads under the sleepers is based on the general theory of base isolation of systems (Figure 10). Using input data, one can assess the performance of the rubber pads using simple dynamic mass and spring models. The parameters affecting the effectiveness are the track mass and stiffness of the base isolation.

The dynamic parameters of the un-isolated system (i.e. fixed at its base), shown on the left side of Figure 10, are defined by the following basic equations for circular frequency of vibration ω_f, vibration period T_f and damping (ξ_f):

$$\omega_f = \sqrt{\frac{m}{k}} \tag{10}$$

$$T_f = \frac{2\pi}{\omega_f} \tag{11}$$

$$\xi_f = \frac{c}{2m\omega_f} \tag{12}$$

The dynamic parameters of the base-isolated system (i.e. not fixed at its base), shown on the right side of Figure 10, are defined by the following equations for circular frequency of vibration (ω_b), vibration period (T_b) and damping (ξ_b):

$$T_b = \frac{2\pi}{\omega_b} \tag{13}$$

$$\omega_b = \sqrt{\frac{k}{m+m_b}} \tag{14}$$

$$\xi_b = \frac{c_b}{2(m+m_b)\omega_b} \tag{15}$$

According to the above equations, the base isolated system has a natural frequency several times smaller than that of the un-isolated system. This approach was further applied to reduce the vibration level at the critical distances of the considered structures in the vicinity of the railway line. The theory of base isolation is generally associated with the transmission factor (TR) [32] which depends on the ratio of the excitation frequency, (ω) to natural frequency of the system (ω_n), Figure 11.

TR is expressed as a function of the ratio of excitation frequency to natural frequency (ω/ω_n), and damping, (ξ) as expressed by the following equation:

$$TR = \frac{\ddot{u}_0^t}{\ddot{u}_{go}} = \left\{ \frac{1+\left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2} \right\}^{1/2} \tag{16}$$

If the (ω/ω_n) ratio is greater than $(2)^{1/2}$, TR is reduced. By applying base isolation, this factor can be reduced to the permissible value of vibration at the source.

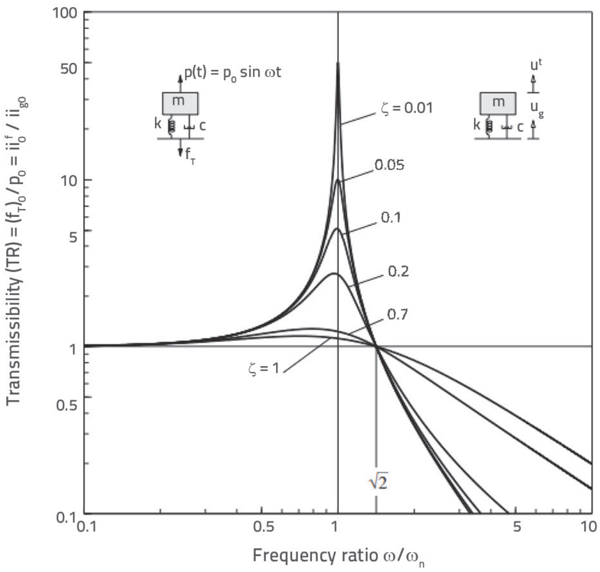

Figure 11. Transmission factor (TR) as a function of the ratio of frequencies (ω/ω_n) and damping [32]

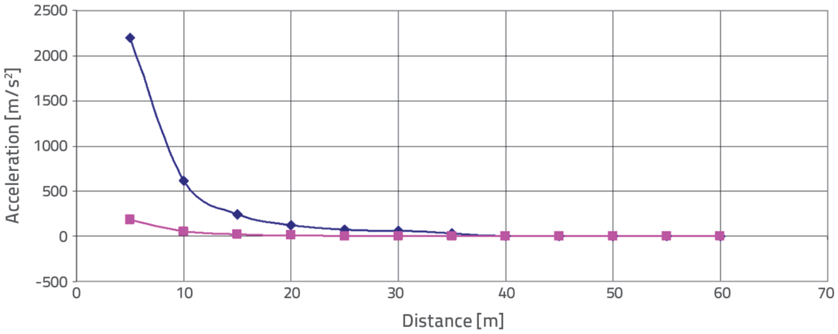

Figure 12. Modified attenuation curves referring to 'RP-3 Romanovce' with non-isolated (blue line) and isolated (magenta line) sleepers

The evaluation of the necessary measures started with the prognosticated vibration levels for the measurement profiles along the railway line using the methodology presented in section 2. According to the attenuation curves, the critical distance at which vibrations are still beyond the permissible level, is approximately 30 m from the source for almost all seven profiles considered along the Kumanovo–Deljadrovci railway line section. The structures were identified in the marked zones (hotspots) in which the permissible limit was exceeded. Based on this evaluation, the necessary isolation of railway sleepers for the reduction of vibrations at these structure locations was computed. More details on these computations are provided in [22]. For the case analysed in the previous section, namely, "RP-3 Romanovce" (km 417+300) where residential houses are situated at a distance of 22–50 m, the attenuation curves proved the necessity of measures for the reduction of the vibration level. By selecting an appropriate elastomeric material for the application of base isolation (i.e. placement of USP) for a conventional train with a load of 225 kN and thickness of 20 mm, the TR was reduced to the required vibration level at the source, as shown in the modified attenuation curves (Figure 12 "RP-3 Romanovce"). At the critical distance of 20 m from "RP-3 Romanovce", the acceleration prior to the application of the measures was 126.7 mm/s^2. Following base isolation of the sleepers, this level was reduced to an allowable 10.37 mm/s^2.

3.2. Further remarks

To apply the numerical procedure for the computation of the necessary characteristics of isolation materials described in section 3.1, further examination by additional measurements through the applied measures is necessary. Eq. (16) can usually define, with a sufficient level of accuracy, the necessary frequency for obtaining the corresponding TR. However, in practice, it is preferable to use the finite element models described in section 2. This includes the variation of elastic-mechanical and geometrical characteristics of the built-in base isolation materials so that the isolated system attains the appropriate natural frequency ω_n. At the same time, the proposed finite element model, can be used directly to obtain the attenuation curve, without the need of obtaining additional measurements. Moreover, the model can be implemented with reduced the number of points at which these measurements need to be performed. In this way, the framework of activities described in section 2 is complemented by the activities described in section 3 to obtain a complete procedure for dealing with the high level of vibrations caused by railway traffic.

4. Conclusions

The proposed integrated methodological approach contains activities that include in-situ measurements and analyses of specifically selected locations in urban and rural media along a railway track. The activities related to defining and verifying the numerical models based on FEM are used to verify the attenuation curves obtained from the in-situ measurements and activities related to the necessary measures for eliminating or mitigating the effects of vibrations on people and nearby structures. Briefly, the conclusions of the investigation are as follows:

- Railway traffic represents an important source of vibrations which may affect the quality of life of people settled in the vicinity of railway lines with frequent traffic.
- Currently in North Macedonia, there are no national guidelines or standards related to the problems associated with the increased level of vibrations from different sources and their effect on nearby structures.
- The objective of the in-situ measurements was to construct attenuation curves (i.e. define the relationship between the accelerations obtained in the study) which represent the mode of measurement for the level of vibrations and distance from the source. The use of appropriate standardized curves (the analysis within the research was completed using Polish standards [13, 33] which are based on ISO standards) creates the possibility of defining a safe distance for structures, i.e. distance at which the level of vibrations would be below the permissible level to be perceived by people.
- The investigations were practically implemented on the railway corridor along Kumanovo–Deljadrovci section. The analysis was based on the experimental definition of attenuation curves at seven profiles along the section and measurements of vibrations caused by passenger and freight trains passing through the village of Brzak. According to the analysis, the ultimate value of vibrations at an acceleration of 10 mm/s^2 is expected to be exceeded in the distance range of 0–20 m, to the left and right of the railway line.
- Numerical modelling and analysis of the critical profile using FEM proved essential in cases where a sizable study for a wider analysed domain is necessary. The attenuation curves obtained through the numerical models and measurements show a logical correlation, which indicates that the parameters of the level of attenuation of vibrations can be numerically predicted for a major part of the treated

region, thus reducing the in-situ measurements and saving considerable resources.

- The proposed integral methodological approach enables necessary measures to be defined for reducing the effects of vibrations for the considered profiles. To predict the response of the system, (i.e. obtain the level of vibrations with defined measures) one can use a simplified computation or numerical model of the existing condition that is appropriately calibrated in compliance with the proposed measures.
- The proposed integrated methodological approach with the steps described provides a sound basis for further investigations in this field.

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