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Train Induced Free Field Vibrations Experimental and Numerical Analysis

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Abstract

The experimental-numerical model for the ground-borne vibrations calculation arising from railway traffic is introduced. The prediction of the free-field dynamic response at the ground distance point (from the railway track) calculation procedures using spectral analysis means using the input experimental of data as described in this paper. The calculation of the ground-borne vibration level at the distance is based on the viscous-elastic soil model [1,2,3,6,7]. At a distance free-field response numerical results are presented using response spectra or power spectral densities (PSD) and the frequency response function (FRF) of the viscoelastic soil medium, [6,8,9,10,11]. In the next step the response spectra at the distance ground point can be applied for the dynamic response of structures (engineering and building) calculation arising from railway traffic using the relevant computational building structure model. The main aim of this paper is to point the related problem of the vibration caused by traffic on surface railways, a subject which has been treated very little up to now.

Keywords: microtremor, railway traffic effects on structures, prediction dynamic half space and structures response models, in situ experimental tests, ground vibration and structure response spectra, spectral analysis.

1 Introduction

The structures of the existent railway have many features, which are capable of supplementing the basic stress field beneath the train. Any unsteady riding of the vehicle such as bouncing, rolling, pitching and yawing must result in additional fluctuating forces on the track structure. Recognized defects such as eccentric wheels, unbalanced wheels and wheel–flats may also contribute to ground disturbance. The track itself does not provide uniform support: the rails, themselves of fixed length, are supported on sleepers placed at regular intervals, and the sleepers are in turn surrounded by and rest upon stone ballast. This ballast bed may by its very nature provide a somewhat variable support, and voids below the some occasional sleeper are well–known faults. All of these track features can be expected to contribute to the stress field present in the ground below and beside the train, and hence contribute to the vibration disturbances, which propagate to the wayside. The experimental evidences point out the impacts from the wheels passing over the rail joints have significant influence on ground vibration transmitted from railway to nearby regions and the spectral characteristics of the ground-borne vibration can be significantly dependent on: (i) a unit train of identical vehicles produces ground vibration at frequencies which are related to wagon length, (ii) vibration which are produced by passing steady wheal load over the discrete support provided by sleepers this effect is independent on inertia effects, (iii) vehicle vibrations (inertia effects) and (iv) track irregularities.

The increasing interest and awareness for the problem of vibrations in the built environment due to traffic among the population and the local and state authorities has triggered off *the need for a better insight in the physical phenomena involved in the problem and for an estimate for the expected vibration levels*. Prediction models for ground vibration from railway train to nearby region involve consideration of two processes: (1) the vibration generation process, and (2) the vibration propagation process. These processes should be treated separately.

Empirical prediction models show a close relationship to a set of experimental data but the application of the model is limited to similar conditions. Also these models do not always provide insight in the influence of specific parameters. Numerical prediction models allow the influence of various parameters to be investigated [8,12,13] but a *validation of the model with experimental data is required to verify the underlying theoretical assumptions.* Even though the validation focuses on traffic induced vibrations, the numerical prediction model can be generally applicable to other types of vibration sources.

An analytical expression for the spectral density of ground vibration as functions of distance from both roadways and railways respectively is formulated in terms of rail and wheel roughness, vehicle characteristics, track–soil interaction forces and the frequency response function for the ground. The use of the random process theory to predict the level of ground vibration in the vicinity of railways via calculation of the spectrum of vibration at half – space point is possible by the two principal ways: ***(i)*** – using a computer implementation of the theoretical expression for the rail roughness spectrum, the vehicle mass distribution spectrum and a model of vehicle dynamics and track–soil interaction and the frequency response function (FRF) of the ground by a method involving integral transform, ***(ii)*** – using average response force spectrum derived from experimental data for authorized railway category with corresponding track profile and the FRF of the ground or *case study* experimental data and calculate response spectrum vibration at point by the same way as mentioned in (*i*). The random process theory in the dynamic ground properties investigation can be utilized as well. Also via the input signal (due to traffic) measurement into the ground and the output signal measurement passing through the ground, *frequency response function, elastic and attenuation characteristics of the ground* can be obtained, [4,15,16].

2 The analytic - experimental prediction models

The literature review [15,17,18] shows that the prediction models still use simplifications to predict the ground–borne vibrations due to railway traffic. The analytical prediction model [22] results have given good agreement with measured ones and are applicable for real engineering needs and it is suitable to be mentioned it here. In this model impacts from the wheels passing over the rail joints are assumed to generate the damped free vibrations in the rail. These generated vibrations are then transmitted to ballast, roadbed and ground. If the frequencies of the generated vibrations are much higher than the natural frequency of the ballast, the input to the ballast is given from the envelope function of the vibration generated at the rail. The ground vibration recorded at a distance from a railway is analysed assuming it to be a random and statistically stationary function of time. Perhaps the most descriptive representation of the traffic influence on a half space is provided by a response spectrum. In proposed procedure we consider the response at a point due to random line excitation it needs to apply spectral analysis theory to predict the level of ground vibration at the distance by vibration spectrum calculation via FRF of the ground.

The analytic–experimental approach suggests the test and the theory data combination to calculate the prediction level of ground vibration. In this process as an input signal can be used accelerations spectra (or spectral densities) derived from experimental data bank for authorized railway category with corresponding rail profile or accelerations spectrum $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$ measured at nearest ground point to the track for individual case study. On the surface of a linear viscous–elastic half space, the displacement response spectrum $S_{ww}(\omega)$ can be expressed in terms to the input spectrum of ground vibration accelerations $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$, [4] by

$$S_{\ddot{w}\ddot{w}}(\omega) = |H(\omega)|^2 \overline{S}_{\ddot{w}\ddot{w}}(\omega), \qquad (2.1)$$

where $|H(\omega)|$ is the frequency response function magnitude for the half space medium and $\ddot{w}(t)$ is vibration accelerations of the surface measured at a distance y from the measured point near the track. In this approach it can be used as the input spectra $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$ measured at nearest ground point to the track. The frequency response function (transfer function) of the ground can be derived via experimental impulse seismic method (ISM) or cross–hole test data, from which *elastic and attenuation parameters of the ground* can be obtained, too. The measuring output response acceleration spectrum at the distance $S_{\ddot{w}\ddot{w}}(\omega)$ due to input accelerations spectrum $\overline{S}_{\ddot{w}\ddot{w}}(\omega)$ the FRF – $H(\omega)$ is possible derived by (2.1), too.

2.1 Case study - ground vibration transmission from a railway

2.1.1 Experimental tests description

An experimental study of ground vibration transmission from a railway was carried out [22], adjacent to the ŽSR railway Bratislava – Vienna, track No.1 (No.2) in Bratislava (BA). The track is straight and well situated on level ground (sandy loam

–3,5m and gravel sand –12,0m). This permits the ground to be modelled as a damped, viscoelastic half space. The viscoelastic model of soil simulation *using the complex modulus conception* → $E^*=E(1+\delta_E)$ and $G^*=G(1+\delta_G)$ respectively, offers a very good approach to the actual soil behaviour (*E, G and* $\delta_E \approx \delta_G$ *are real and imaginary components of complex modulus*). The basic equations used to describe the viscoelastic half space analysis of wave propagation through ground with modulus in complex form cannot be fully described here, see [2],[7]. The *Raleigh's and shear waves propagation* in half space are analysed in this form in [3].

The experimental tests for the purpose of the evaluation of elastic and attenuation soil parameters were performed at the test site. The ground vibrations due to train were measured at the test site adjacent to the track at distances of 3,0(7,3)m, 13,0 (17,3)m and 23,0(27,3)m respectively by accelerometers BK – 8306 (Brüel – Kjaer). The accelerometers and impulse positions are plotted in Figure 2.1. The output signals from the accelerometers were preamplified and recorded on portable PC equipped with A/D converters software packages *NI* and *DISYS*. The experimental analysis has been carried out in the *Laboratory of the Department of Structural Mechanics, University of Žilina.* The ground vibrations frequencies were obtained using spectral analysis of the recorded soil response dynamic components, which are considered ergodic and stationary. Spectral analysis (spectra, PSD) was performed via *National Instrument* software package *NI LabVIEW*. The wave velocities have been investigated by means of the correlation and spectral analysis in order to obtain cross correlation functions $R_{xy}(t)$ and coherence function $\gamma_{xy}^2(f)$.

Vibration propagation process experimental spectral analysis. The object of the experimental measurements was to find: spectral characteristics of the vibration components of the track near region soils by the acceleration power spectral densities $G_{ii}(f)$–input PSD, $G_{kk}(f)$–output PSD, $G_{ik}(f)$–cross PSD, and the soil frequency characteristics expressed by the frequency response function $H(f)$ or by gain factor of the response function $|H(f)|$, respectively. The pickups positions are shown in Figure 2.1. The roadbed and ground accelerations of the vibrations were recorded using portable notebook computer with relevant software and hardware facilities. As an example, one of the spectral analysis results (PSD) of the vibrations accelerations induced by train in the ground at measured point BK1 is shown in Figure 2.2. From experimentally obtained accelerations time histories – $\ddot{w}(t)$ and spectrum – $\overline{S}_{\ddot{w}\ddot{w}}(f)$ or PSD – $G_{ii}(f)$ of ground vibration at the track nearest region is possible [4] to calculate by eq.→ $G_{kk}(f) = H(f)G_{ii}(f)$

i) the response spectrum $S_{\ddot{w}\ddot{w}}(f)$ or PSD – $G_{kk}(f)$ at the distance point on the surface of a linear viscous – elastic half space via FRF of the ground (from ISM impulse tests),

ii) the FRF–$H(f)$ of the ground medium via input–$G_{ii}(f)$ and output–$G_{kk}(f)$ PSD measured at the track nearest region and at the distance point respectively.

2.1.2 Experimental tests results at nearby track region

The object of experimental measurements [22] of stationary signals *due to moving trains* was to find:

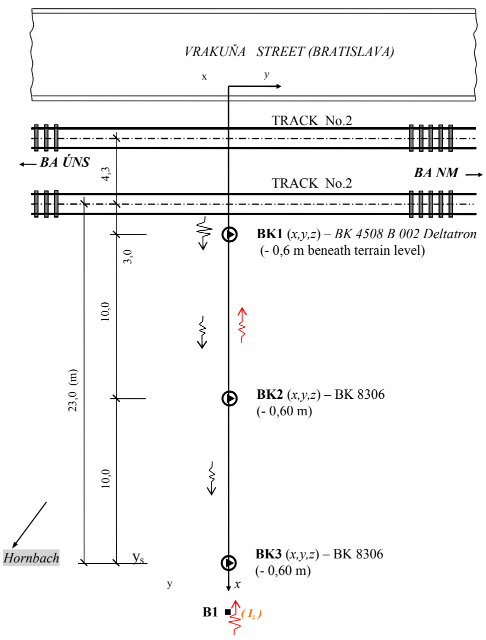


Figure 2.1 The pickups positions in BA Trnávka track region

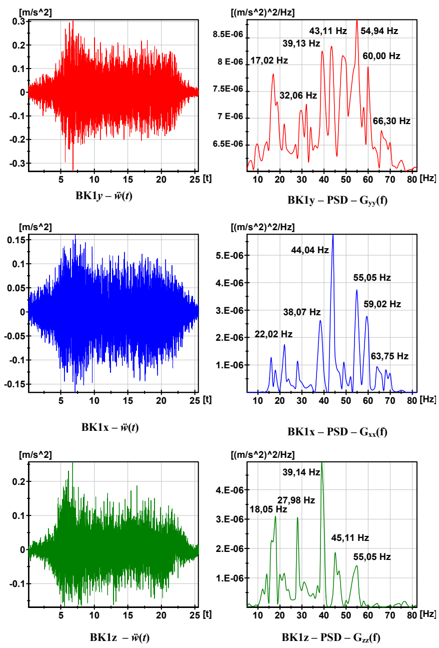


Figure 2.2 The accelerations and PSD of ground vibration at BK1

- the soil frequency characteristics FRF–$H(f)$ expressed by the vibration accelerations PSD – $G_{ii}(f)$, $G_{kk}(f)$,
- the Raleigh's and shear wave velocities v_R *and* v_s by *cross correlation function* $R_{xy}(\omega)$, then derive the initial shear modulus $G_0 = v_R^2 \rho F_{RE}$, where F_{RE} is a real component of complex roots of frequency equation [7], and ρ is mass density of soil,
- the *attenuation coefficient* α (m^{-1}), obtained by *standard deviations* $\sigma(0)$, $\sigma(y)$ of displacement amplitude vibration at the distances l_0, l_y from source of excitation using the *displacement power spectral densities* $G_{ii}^{(0)}$ and $G_{kk}^{(y)}$. The coefficient of attenuation is then defined as follows

$$\alpha = \left(l_y - l_0\right)^{-1} ln\left(k\sigma_{(0)} / \sigma_{(y)}\right); \quad k = \left(l_0 / l_y\right)^{1/2}. \qquad (2.2)$$

The results of the stationary signal tests are as follows,[23]:

- $v_R = 160.20\ ms^{-1}$; $\delta_G = 0.092$; $E_0 = 141.60$ MPa; $G_0 = 51.32$ MPa,
- the dominant frequency bands are evident from inputs PSD at the point B3 on Figure 2.2 (Test No.5 – fast train, 95,0 km/h).
- the input and output PSD at the point B3 and soil FRF are shown on Figure 2.3 (Test No.12 – bulk granular materials train, 76,0 km/h).

The calculation includes the data: $\lambda_R = 10.8$ m, $\rho = 2000\ kgm^{-3}$, $F_{RE} = 1.0695012$, $\nu \approx 0.38$ (Poisson ratio) and by (3.2) $\alpha = 0,0267(m^{-1})$.

An approximate relationship between damping parameters $\delta \approx \delta_G \approx \delta_E$ and length λ_R of the *Raleigh's* wave is $\delta \approx |\alpha|\, \lambda_R / \pi$.

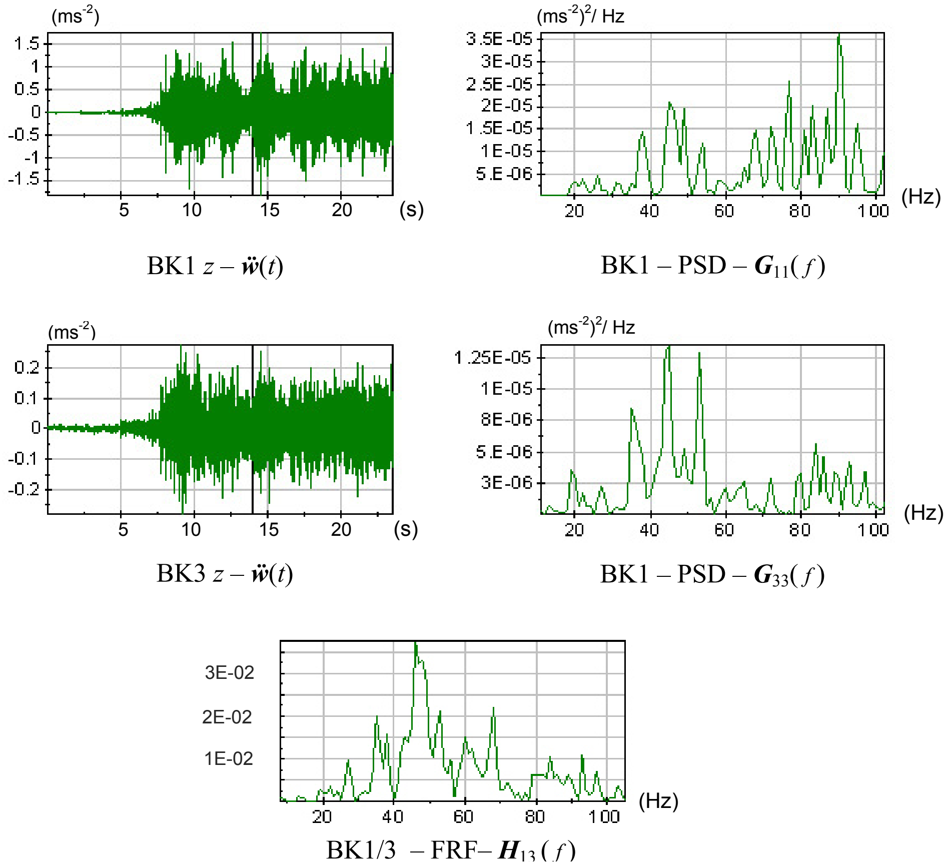


Figure 2.3 The accelerations time histories, PSD and FRF of ground vibration at points BK1, BK3 due to train of Bulk Carriers of Granular Materials, (76.0 km/h).

2.2 Case study – ISM tests nearby the building region

2.2.1 The impulse test description.

It is common practice in the ISM are used two or more receivers located at distance l_i (m) from source. Waves propagation generated by the source is monitored with receivers (BK1, BK2) at the same depth as the source, (Figure 2.5). The traditional approach used in the in situ tests to determine shear wave velocity (v_s) is based on identifying the time interval of the wave travelling between e.g. the first (BK1) and second (BK2) receiver. Once these times are determined, velocities are calculated via dividing distance (l) by appropriate times. Wave velocities determined by source to receiver measurements are termed *direct velocities method*. Other techniques based on correlation and spectral analysis theories was used [4] to determine body wave velocities in the ISM test.

The experimental ISM tests in situ were performed, [23] by the impact device (dynamic loading plate DLP, Figure 2.4), This device consists of the circular rigid plate (1) with the contact area A = 1000.0 cm^2, dropping weight (2) with mass Q = 12.5 kg, indention for setting the height of the weight (3), springs (4), plunger (5) guide rod (6) casing (7) and safety pin (8). In each dynamic test there were carried out 6 impulses in the measured spot caused by dropping weight from constant height h. The height h was set experimentally to achieve the constant area impact stress p = 0.22 MPa. In the ISM common practice the dynamic impulse into the halfspace is carried out by DLP and the propagation of surface waves generated by the source is monitored via receivers (Bi, Bi+1) at the same depth as the source.

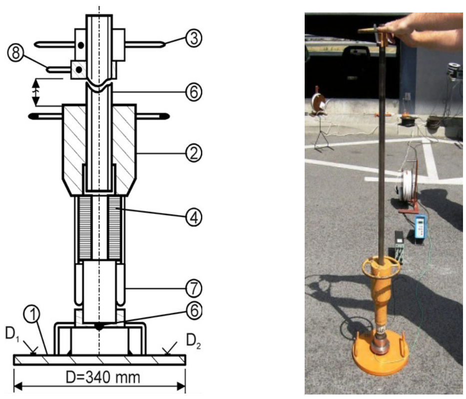
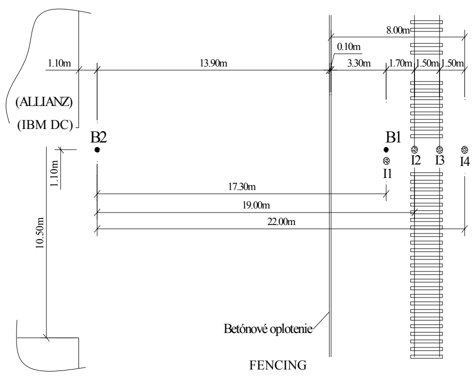


Figure 2.4: Dynamic loading test device – DLP

2.2.1 Experimental tests results at nearby the building region

To calculate prediction vibration level and dynamic response for projected new building in a new railway line area *it was needs to know the building site soils dynamic parameters and FRF*. The in situ impact tests at the IBM Data Centre building site were performed [21,23]. The building site is situated in the same area in which the new Trans European Network (TEN–T) line is projected, too. After the both structures erection the distance between by them will be approximately 20 m, than the prediction of building vibration level and response spectra due to operating trains



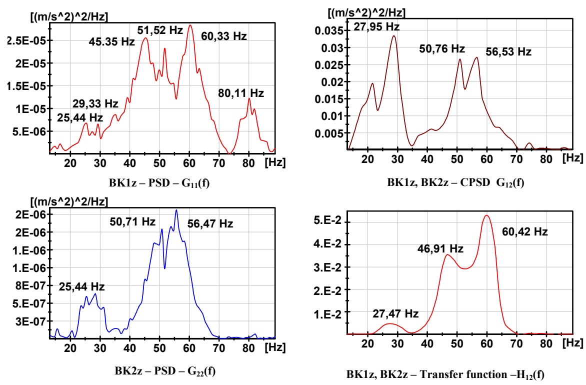


Figure 2.5: Accelerometers and DLP (I1– 4) position at projected building

Figure 2.6: The ISM5 test spectral analysis results in B1 and B2 points

was required. The IBM building site layout and accelerometers and impact loading (DLP) position during the experimental tests are shown in Figure 2.5.

The object of experimental measurements of transient signal was to find:

- the Raleigh's and share wave velocities by using standard equipment of ISM,
- the same dynamic characteristics as mentioned in stationary signals investigation (at nearby track region) via the spectral and correlation procedures. The impulse test results are as follows:
    - v_R = 145.10 ms^{-1}; δ_G = 0.117; E_o = 109.20 MPa; G_o = 41.10 MPa,
    - the ISM test No.5 spectral analysis results example is shown on the Figure 2.6.

The calculation includes data: λ_R = 9.2 m, ρ = 1950 kgm^{-3}, α = 0,0398(m^{-1}), F_{RE} =1.061457 and υ = 0.33.

5 Conclusions

This paper presents an overview of numerical prediction model for the ground–borne vibrations at the distance point of the visco elastic halfspace due to railway traffic. The numerical and numerical–experimental approach for "the ground response at a distance" calculation procedure were introduced. Based on the results presented in this paper the following conclusions can be drawn:

- The numerical-experimental prediction model: The ground vibration recorded at a distance from a railway is analysed assuming it to be a random and statistically stationary function of time. The analytic–experimental approach process proposes the test and the theory data combination to calculate the prediction level of ground vibration. In this process as an input signal can be used input spectra (accelerations or spectral densities) derived from experimental data bank for authorized railway category with corresponding rail profile or accelerations spectrum $\overline{S}_{\ddot{w}\ddot{w}}(f)$ measured at nearest ground point to the track (case study). The modelling of the soil as a viscoelastic half-space represents the key feature of the prediction model. This soil model is used both for the evaluation of the track–soil interaction forces as well as for the prediction of the ground–borne vibrations.
- The proposed procedure allow to derive the FRF– $H(f)$of the ground medium using output response acceleration spectrum at the distance $S_{\ddot{W}\ddot{W}}(f)$ and input accelerations spectrum $\overline{S}_{\ddot{w}\ddot{w}}(f)$ measured in situ. Also utilisation of this procedure the elastic and the attenuation parameters of the ground can be obtained, too.

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