Prediction of Ground Vibrations Induced by Urban Railway Traffic: An Analysis of the Coupling Assumptions Between Vehicle, Track, Soil, and Buildings

Georges Kouroussis

Université de Mons – UMONS, Faculty of Engineering, Department of Theoretical Mechanics, Dynamics and Vibrations, Place du Parc, 20 — 7000 Mons, Belgium

Laurent Van Parys

Université de Mons – UMONS, Faculty of Engineering, Department of Civil Engineering, Place du Parc, 20 — 7000 Mons, Belgium

Calogero Conti and Olivier Verlinden

Université de Mons – UMONS, Faculty of Engineering, Department of Theoretical Mechanics, Dynamics and Vibrations, Place du Parc, 20 — 7000 Mons, Belgium

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This paper is concerned with the problem of ground vibrations induced by railway traffic and its modelling through a decoupled approach, using only the finite element modelling for evaluating the ground waves propagation. The vehicle/track dynamics is calculated separately. An important modelling aspect is undoubtedly the track/soil interaction, which can play an important role in the generation of seismic waves. To avoid excessive computational resources, a coupled lumped mass model (CLM model) of the soil has been recently developed and is considered in this study. The influence of ballast and soil stiffnesses is presented, in order to confirm the range of validity of the CLM model. Combined with a discrete two layer model of the track, it offers the possibility of working with a simple compound track/soil model. A comprehensive analysis is provided to show the benefit of the finite element model with the proper radiation conditions at infinity, for analysing the structural response of a building located in the vicinity of the track. Focusing on typical results based on the tram of Brussels, the effects of track/soil and soil/structure coupling are investigated. Modal analyses of the vehicle and the building are presented in order to understand the effects of seismic wave amplification, especially when the source contains frequencies close to the natural frequencies of the building.

1. INTRODUCTION

Problems related to vibrations in buildings represent an important environmental issue in network designs, especially for nearby structures in densely populated cities. Ground vibrations induced by road and railway traffic can cause nuisance to occupants, malfunctioning of sensitive equipment (surgery or high-tech production), and even damage to buildings, if the vibration level exceeds critical values (e.g., $5\,\mathrm{mm/s}$, according to DIN 4150 standards[1]). The growing traffic volume, the higher population density, and the diminishing distance between the vehicle and the structure amplify the overall vibration nuisance. Although most of general traffic exposure vibrations (smooth surface) are not uncomfortable for people, the passing of heavy vehicles on a road or track with an uneven surface is often pointed out as the main vibratory nuisance felt by city residents.

Brussels, the capital of Belgium and of the European Union, is comprised of a heavily urban territory with over one million residents. The railway network in the Brussels Capital Region ($160\,\mathrm{km}^2$) consists not only of the urban tramway network but also of the intercity and international train lines, since it represents a vital link in the high speed train (HST) network in the northwest of Europe. Although railway transport appears as the most promising solution to traffic congestion, the development of new lines is confronted with the availability of convenient areas and the mistrust of the dwellers likely to be submitted to new nuisances. These difficulties have been largely encountered during the implementation of the new suburban light rail network. Presently, the tramway represents 25% of urban transport in Brussels.

The accurate prediction of railway–induced ground vibrations, and of the associated structural response, needs an understanding of the complex mechanisms of the generation and propagation of seismic vibration waves. The usefulness of a numerical prediction model has been well emphasized by various authors during the last decades. Empirical models, derived from in situ measurements, and commonly used at the very beginning, have been replaced by numerical models, which are more general and not limited to situations covered by the in situ measurements. Crispino and D'Apuzzo[2] recently described the measurement of road traffic-induced vibrations on a heritage building in Naples, which conducted an empirical prediction expression of peak particular velocity. This study takes into account the maximum height or depth of the localized surface irregularity over which the heavy vehicle passes, the speed of the vehicle, and the distance between the irregularity and the building. Vogiatzis[3,4] has studied the effect of ground-borne vibrations generated by the metro of Athens on ancient monuments. The results were obtained from the bidimensional finite element model using experimental data, in order to propose efficient mitigation solutions. Track/soil and soil/structure interactions can also be studied from the experimental data, using measured frequency transfer functions coupled with a numerical vehicle/track model.[5,6]

To date, most of the existing numerical methods are based on wavenumber transforms, working in the k–ω domain and allowing an efficient representation of the infinity.[7–9] Nevertheless, the main drawback of these methods is the difficulty to include complex geometries in the model, like embedded structures. In addition, the problem statement is analogous in earthquake engineering, but the frequency content is larger than the one of typical earthquakes (generally under 10 Hz, while traffic-induced vibrations are felt up to 100 Hz). Pyl et al.[10,11] have proposed a numerical method based on the boundary element method coupled with the substructuring finite element model for soil/structure calculation, with an alternative formulation to mitigate fictitious eigenfrequencies borrowed from an original method for acoustic problems. The use of a full finite element (FE) model is more scarce, due to the difficulty of defining the correct absorbing boundary conditions to avoid spurious reflections at the model boundary. For example, Ju[12] has investigated the capacity of the FE approach to simulate the behaviour of vehicle–induced vibrations, proposing a solution for modelling moving elements like wheels on the ground. Large FE models, including the building, are proposed, implying however excessive computational resources and CPU-time.

According to the authors' opinion, the railway-induced ground vibration is analogous to the vibration isolation concepts. When a mechanical system is subjected to a force $f(t)$, a part of this is transmitted to the foundation, depending on the characteristics of the isolation (Fig. (0a)). On the other hand, when the foundation undergoes motion $u(t)$, the equipment also moves, with motion $x(t)$ depending on the equipment-isolator system (Fig. (0b)). In the railway, the first case is associated with the vehicle/track/soil interaction, as the force is defined by the wheel/rail interaction, with the static and dynamic contributions. The track plays the role of isolator by dispatching the forces through the discrete supports (sleepers).

The second case is the soil/structure interaction, with eventual mitigation solutions defining the isolation between the soil and the building. These two concepts are coupled, since the foundation is flexible. Although the connection of the vehicle with a flexible track does not appear with an insurmountable difficulty (see, for example, the works of Dietz et al.,[14] which use the co-simulation method of coupling the multibody and finite element approaches), the coupling with the subgrade imposes some restrictive constraints, due to the methodology employed for modelling the ground:

- In vehicle dynamics, the dynamic simulations are essentially performed in the time domain (essentially with the multibody approach), allowing the assumption of nonlinear behaviour of elements. A possible modal analysis needs, however, the knowledge of eigenvalues and eigenvectors related to the equations of motion, and is associated with a frequency analysis (linearisation around the nominal positions). Nevertheless, the existing methods for ground modelling often impose the simulation domain the frequency analysis for the classical boundary element method, and the time analysis for the finite element method proposed in Kouroussis et al.[15]

- The current computation time required by the multibody software is relatively low. It is known nowadays that the simulation time in soil dynamics is significant, especially for three-dimensional problems with a moving source (inducing a particular modelling of the contact behaviour).

- A periodic representation along the track is often adopted in the track/soil model, allowing for a reduction in computational efforts with the help of an efficient 2.5D approach,[16] but useless if local configurations must be considered in the vehicle/track model (e.g., wheel/rail contact in a rail joint).

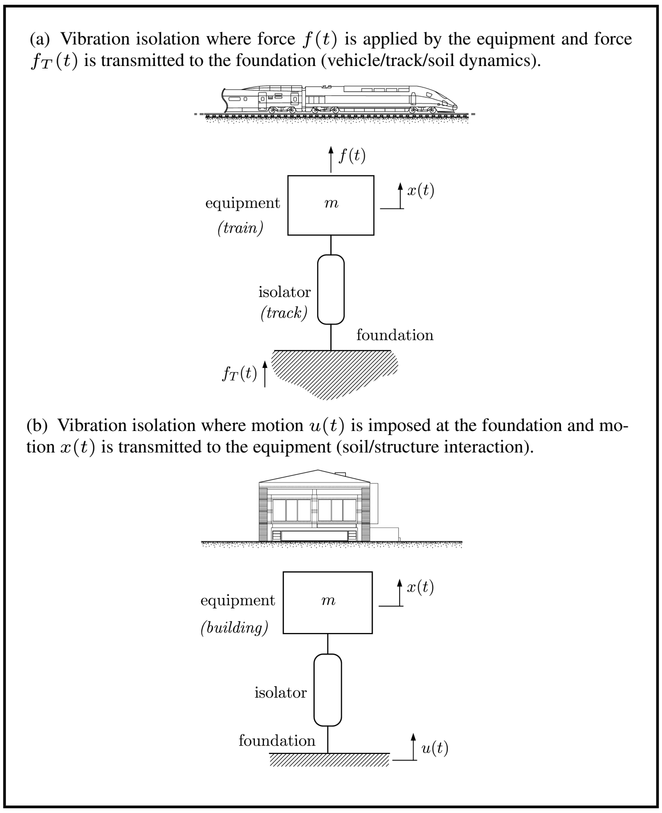


Figure 1. Schematic diagrams of the vibration isolation systems: an analogy with the railway-induced ground vibration, adapted from[13].

This paper investigates the abilities of FE analysis to characterize building vibrations induced by adjacent tramway network with an important rail unevenness (local defect). The retained example concerns the tramway network in Brussels. A prediction method is used in this case, thoroughly validated in the past.[17,18] The purpose of this finite/infinite element model,[17] and the dynamic soil/structure interaction, at the source and the receiver is here accounted for. In addition, the building is analysed with the FE approach, in order to determine its natural frequencies. The same operation is performed

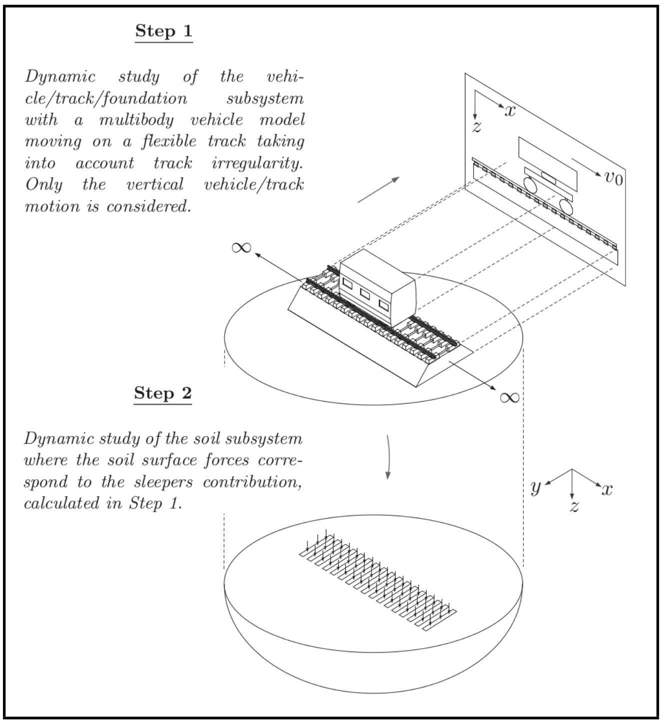


Figure 2. The description of the proposed prediction model, according to a decoupling between the ballast and the soil.

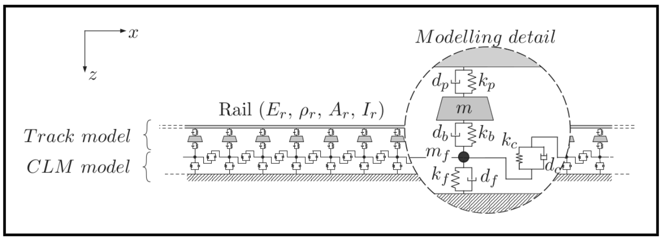


Figure 3. The flexible track, taking into account the condensed soil.

for the vehicle, using the multibody approach, in order to verify if the natural frequencies of the tram coincide with those of the building.

2. PREDICTION MODEL BASED ON A TWO-STEP APPROACH

Recently, Kouroussis et al.[19] proposed a numerical model for predicting the vibration induced in a neighbourhood by a railway vehicle. The particularity of the methodology is based on a two-stages approach, simulating separately the vehicle/track/foundation subsystem and the soil subsystem (Fig. (2)). The first step provides the dynamic behaviour of the vehicle/track/foundation subsystem. The second stage concerns the soil whose free-field response is computed from the loads acting on the soil surface, issued from the first subproblem. The FE method is used in this case, using both infinite elements and viscous boundaries as non-reflecting boundaries, in order to mimic the infinite dimensions of the soil.[20] Both simulations are performed in the time domain. Since each method has specific advantages and shortcomings, it is consequently more interesting to work in two successive simulations to take advantage of their peculiarities; thus, a decoupled approach is proposed. Let us note that the foundation dynamic properties are included in the vehicle/track/foundation with the help of the recently developed coupled lumped mass model (CLM model).[21]

The CLM model is an extension of the well-known Winkler model, which better represents the track soil coupling. An illustrative study is also presented, based on the analysis of track receptances. Finally, the case study findings regarding the ground vibrations are described, with an example coming from the Brussels railway network.

2.1. The Coupled Lumped Mass CLM Model

The mechanical vehicle/track/foundation model (Fig. (3)) that has been recently proposed by Kouroussis et al.[21] is succinctly discussed in this paper. The flexible rail is described by its Young's modulus E_r, its geometrical moment of inertia I_r, its section A_r, and its density ρ_r. Viscoelastic properties are considered for the railpads and ballast, characterised by springs and dampers (k_p and d_p for the railpad, k_b and d_b for the ballast). The CLM model for the foundation is based on the extension of Lysmer's analogue foundation. Besides the foundation mass m_f, stiffness k_f, and damping d_f, additional spring/dashpot systems by means of stiffness k_c and damping d_c are added between adjacent foundation masses for the coupling between each sleeper/foundation contact area. Reduced expressions of transmissiblity have been developed for determining the value of these five parameters. It appears also that damping d_c can be negative for adjusting the ground wave propagation delay.[21]

2.2. Accuracy of the Model on the Track/Soil Coupling: Analysis of the Track Receptance

In order to evaluate the accuracy of the CLM model, track receptances are calculated for a typical track configuration. They correspond to the frequency response functions between the vertical displacement of the rail and the vertical force applied at the same point.

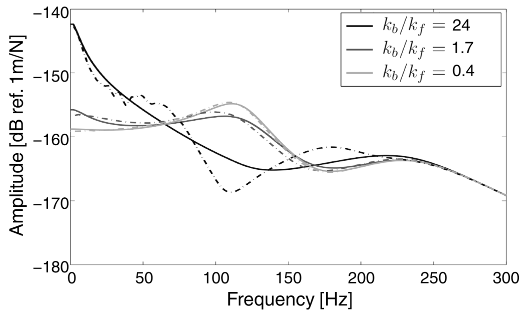
Figures (3a) and (3b) compare the receptances obtained by the CLM model and a rigorous FE model for various k_b/k_f ratios, considering the variation of k_f and k_b, respectively. Figure (4) points out the influence of the stiffness difference, as frequencies of first and second modes, corresponding to in-phase and out-of-phase vertical motions of rail and ballast, depend on the value of k_b, and, to a lesser degree, on the value of k_f (for soft soil). A good correspondence between the two approaches is also observed. Particularly, in the case of soft soil where the track receptance strongly depends on the foundation characteristics, the curve obtained with the CLM model follows the exact solution up to 50 Hz.

3. CASE STUDY: THE TRAM T2000

3.1. Context of the Study

This analysis concerns the vibrations induced by the passing of the Tram T2000, which serves urban districts in Brussels. This vehicle is composed of three coaches: a large one on each end (with a leading bogie), and a small one in the middle (Fig. (5)), with the particularity of large unsprung masses, which is due to the motor placed inside the rotating wheels.

(a) For various foundation stiffnesses (ballast stiffness $k_b = 120\,\mathrm{MN/m}$).



(b) For various ballast stiffnesses (foundation stiffness $k_f = 70\,\mathrm{MN/m}$).

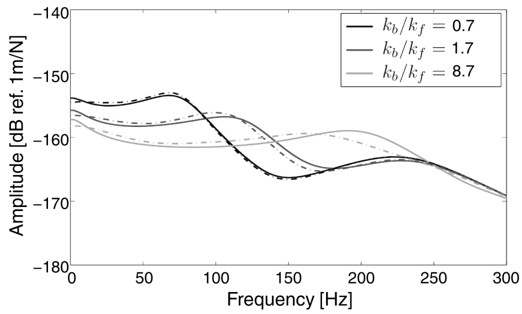


Figure 4. A track receptances comparison, as a function of the ballast/foundation stiffness ratio, and a comparison of the CLM model (dashed lines) with the rigorous FEM model (solid lines).

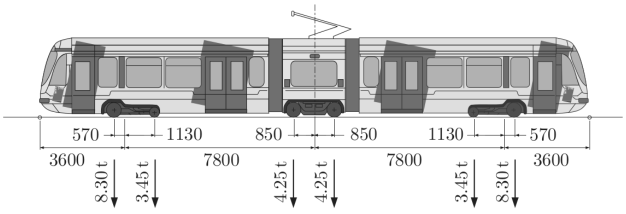


Figure 5. The general configuration of the Tram T2000.

The Brussels tramway network consists of 39% ballasted tracks, 18% clinker pavement, and 28% natural soil pavement. The selected site, Haren, is ballasted and has the advantage of having been previously studied in great detail. The appendix presents all the parameters (vehicle, track, soil) related to the present study.

Regarding the track, it is composed of an EB50T Vignole rail, regularly supported by wood sleepers. The railpad and ballast dynamic parameters (mass, stiffness, and damping) were obtained by updating the numerical vertical receptances from the experimental ones. Various experimental setups were used:

- impact tests realized with hammers impact or falling weight (Fig. (5a));
- harmonic tests through an unbalanced motor (Fig. (5b)), ideal for characterising the low-frequency behaviour;
- and static loading with the help of a driving machine (Fig. (5c)), applying a controlled force on the track (track settlement value).

The experimental set-up for evaluating the ground vibrations is presented in Fig. (7). Due to the difficulty of accurately modelling a rail joint, especially for the contact law, pads have been used to represent local defects, as seen in Fig. (6a). Two sensors have been used for the soil vibration recording, one at $2\,\mathrm{m}$ from the track, as seen in Fig. (6b), and one at $8\,\mathrm{m}$.

(a) Impulse machine.

(b) Unbalanced motor.

(c) Static loading.

Figure 6. The means of characterisation of the track at the Haren site.

Singular rail surface defects are of practical significance in urban railway-induced ground vibrations because they represent the main contribution to the vibratory nuisance, the low vehicle speed that limits the quasi-static effect of track deflection. Pads used in the experimental set-up are chosen due to their ability to represent an equivalent realistic local defect. The main advantage is to easily model its dimension profile, taking into account the wheel geometry. Figure (7a) shows the curve defined by the wheel/profile contact height with the corresponding spatial frequency spectra, which can be seen in Fig. (7b). With this kind of defect and at low speed, frequencies up to around $50\,\mathrm{Hz}$ are equally excited (at a tram speed of $30\,\mathrm{km/h}$, a spatial frequency of $8\,\mathrm{m}^{-1}$ corresponds approximatively to a frequency of $70\,\mathrm{Hz}$).

(a) Pad placed on the rail head, representing the local defect.

(b) Sensor placed in the free-field (at 2 m from the track).

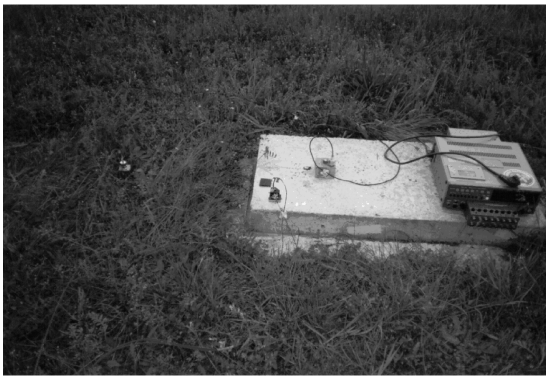
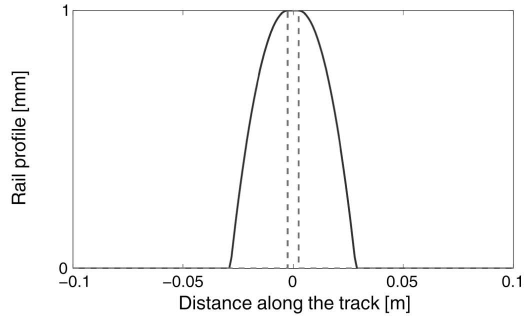


Figure 7. The measurement set-up during the experimental analysis.

(a) Spatial representation.



(b) Spectral representation.

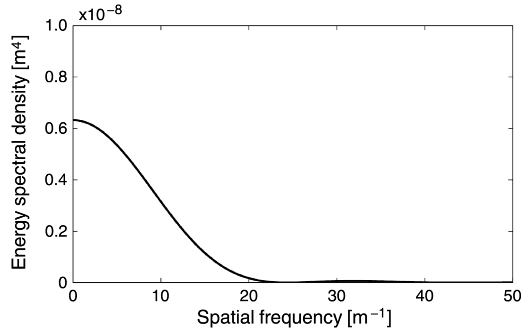


Figure 8. A quantitative analysis of the singular rail surface defect (dashed line: geometry of the rail defect at a height of 1 mm and a length of 5 mm; solid line: wheel/profile contact height taking into account the wheel curvature, where $R = 0.340\,\mathrm{m}$).

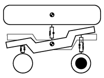
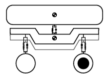
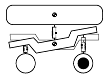
3.2. Theoretical Modal Analysis of the Vehicle

At this stage, it is interesting to quantify the effect of the vehicle dynamics on the wheel/rail forces, which represents the source of ground vibrations. The Tram T2000 presents the particularity of having bounce and pitch motions in a relatively wide frequency range at different natural frequencies, depending on the bogie type. The leading and the middle bogie present some differences: four motorized wheels for the middle system instead of two for the leading bogie (outer side). Figure (9) shows the vertical impedances of the bogie and the car body frame, when excitation is applied on the front wheels. These curves reveal the influence of the car body-on-suspension bounce mode (between 2 Hz and 3 Hz) and the bogie bounce mode,at around 20 Hz, on the car and bogie motions, respectively. Amplitudes of the response are comparable for leading and middle bogies.

Table 1 presents the vehicle modal analysis results (leading bogie) in order to analyse the effect of the vehicle dynamics under a rigid track or a flexible track. Car-on-body bounce mode, bogie bounce mode, and bogie pitch mode are displayed, with the corresponding natural frequencies f_{0i} and damping ratios ξ_i. The effect of the track flexibility is directly observable on these results. In particular, a decrease from 5 to 20% of the frequency f_0 of the first three modes is observed with the flexibility of the track, demonstrating the strong dependence of vehicle/track coupling in vehicle dynamic analysis. Similar observations are noteworthy for the middle bogie, with a notable influence of the bogie bounce mode.

The impedances of wheel on rail control the dynamics of their interaction. Figure (10) shows the frequency content of

Table 1. The theoretical mode shapes of Tram T2000 in the leading bogie.

	 car bounce mode	 bogie bounce mode	 bogie pitch mode
With rigid track	$f_{01} = 1.8\,\mathrm{Hz}$ $\xi_1 = 32\%$	$f_{02} = 24.7\,\mathrm{Hz}$ $\xi_2 = 15\%$	$f_{03} = 33.9\,\mathrm{Hz}$ $\xi_3 = 6\%$
With flexible track	$f_{01} = 1.7\,\mathrm{Hz}$ $\xi_1 = 32\%$	$f_{02} = 20.4\,\mathrm{Hz}$ $\xi_2 = 14\%$	$f_{03} = 26.6\,\mathrm{Hz}$ $\xi_3 = 8\%$

the motor wheel impedances (excitation and response on the wheels), for leading and middle bogies, considering a complete vehicle/track model, with a rigid or a flexible rail. It appears again that the track flexibility plays an important role in the impedance magnitude, which is crucial to an understanding of the wheel/rail interaction. With a flexible track, the wheel impedances decrease in level, with some variations around vehicle natural frequencies up to 70 Hz, which corresponds to the first resonance frequency of the track.[17] Similar results are also obtained with the trailer wheels. The impedance difference, along with the modal analysis results, demonstrates, among other things, the necessity of the vehicle/track coupling in the vehicle and track dynamics, especially when the track presents important roughness or irregularity. The wheel impedance plays an important role in the understanding of wheel/rail interaction. For example, if the wheel impedance is smaller than the one related to the rail at the contact point, important vehicle motions can be developed during the passing of the vehicle on local defects like rail joints, and the wheel/rail coupling cannot be neglected. By comparing these wheel impedances with the defect amplitude spectra displayed at Fig. (7b), we conclude that all modes of the vehicle affecting the wheel impedance are potentially excited when the vehicle rides at low speed on the singular rail surface defect.

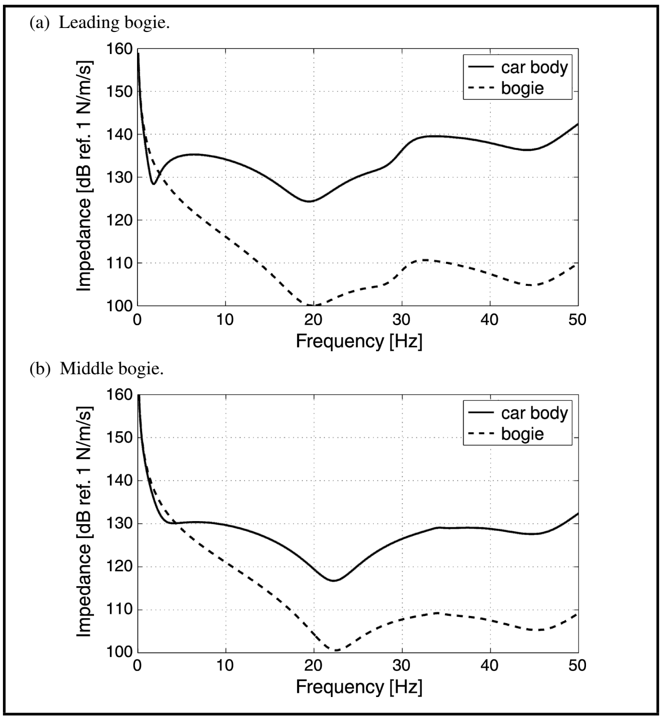


Figure 9. Numerical impedances of the studied tram (excitation on the front wheels).

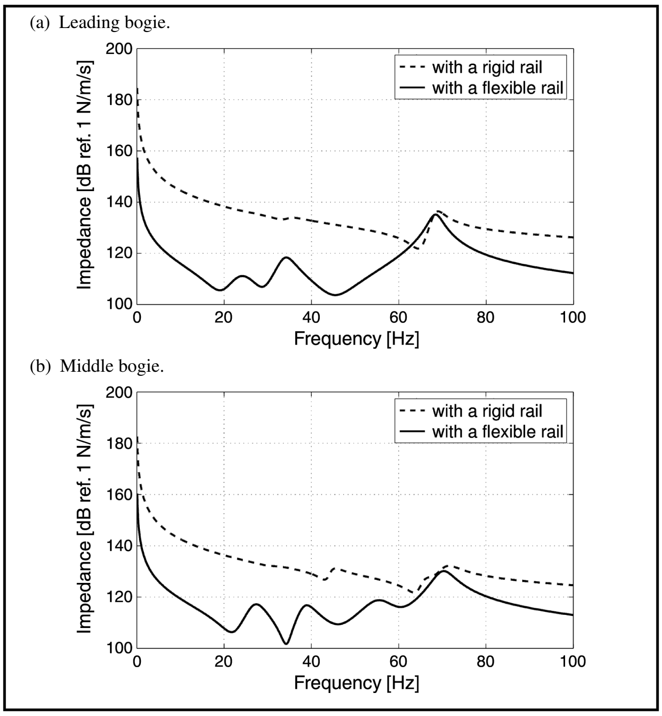


Figure 10. The numerical spectral content of the direct motor wheel impedances.

3.3. Free-Field Ground Response

The full Tramway T2000 is simulated in a straight line. The proposed model has been validated for this study case in recent analyses,[17,18] considering free-field vibrations and the simple assumption of the Winkler hypothesis for the foundation concerning the vehicle/track subsystem. Beside the good correspondence obtained between the predicted and measured responses, it has been demonstrated that vibrations of the soil are essentially dominated by bogie pitch mode and, to a lesser degree, by the car body-on-suspension bounce mode, the bogie bounce mode, and the axle hop modes. Soil stratification has also been pointed out as an important modelling parameter associated with vibration levels. The present analysis mainly deals with the interaction of the wheels with rough rail, to check for the soil surface vertical motion, and to compare the possible difference between the two versions of the model with the Winkler and the CLM foundations. Regarding the soil motion calculation, the computational time reaches up to 17 hours for 10 s simulated time using an i–7 computer and hyper-threading technology (the physical four cores constituting the processor can be virtually doubled during the simulation), and this for an explicit scheme. Similar CPU-times were needed for the vehicle/track/foundation model, using, in this case, the implicit Newmark-$1/4$ integration scheme.

Figures (11) and (12) present the results obtained by the simulations (with a Winkler model and a CLM model for the foundation behaviour) and the corresponding experimental results, at speed $v_0 = 30\,\mathrm{km/h}$ on a local defect, besides considering the overall track irregularity. The vibration of the soil is generally described by its velocity, as many standards for vibration use velocity as a primary vibration descriptor of foundations. Some differences clearly appear between the two numerical results, due of course to the track coupling. But the difference is small, and both numerical results are close to the experimental counterparts, proving that the decoupled approach was valid in this case[19] ($k_b/k_f = 0.26$ with k_f the equivalent Winkler foundation stiffness) and is now improved by the CLM model, which can more accurately represent a rigorous model without decoupling. A background noise appearing in the measurement, whose origin is unfortunately unknown, lightly masks the phenomena.

3.4. Modal Analysis of the Building

A building is modelled by finite elements and is representative of typical private, one-floor houses erected during the 20$^{\text{th}}$ century. It is composed of reinforced cast concrete and masonry. For the calculations, all the materials involved in the model are supposed to exhibit a linear elastic behaviour. The properties of concrete are in accordance with EN 1992-1 Eurocode standard for concrete structures design (see appendix).

The various vibration modes of the structure in the range of 0–50 Hz are depicted in Fig. (13), with a special focus around 20 Hz. Notice that, due to the symmetry of the building, only half of the structure is displayed. All the displayed modes appear as a combination of flexural and torsional motions of walls and floor, and only the mode at 15.0 Hz can be defined as symmetric. The first vertical bending mode of the upper floor is clearly shown at around 15 Hz, while the flexural motions of walls and other bending modes cover frequencies around 25–30 Hz. More particularly, the secondary bending modes are at 23.8 Hz and 27.0 Hz. Line nodes are presented in mode shapes (Figs. (12c)–(12e)), essentially located at the floor symmetry axes, e.g., in the middle of the first floor, modes at 23.8 Hz, 25.5 Hz, and 27.0 Hz have zero amplitude. All these results are obtained by considering the foundations to be fixed.

Indeed, the presented soil FE model is only dedicated to time domain simulations, since the frequency analysis is not accurate enough, according to the meshing guidelines suggested in.[20] Nonetheless, transient analysis can be performed

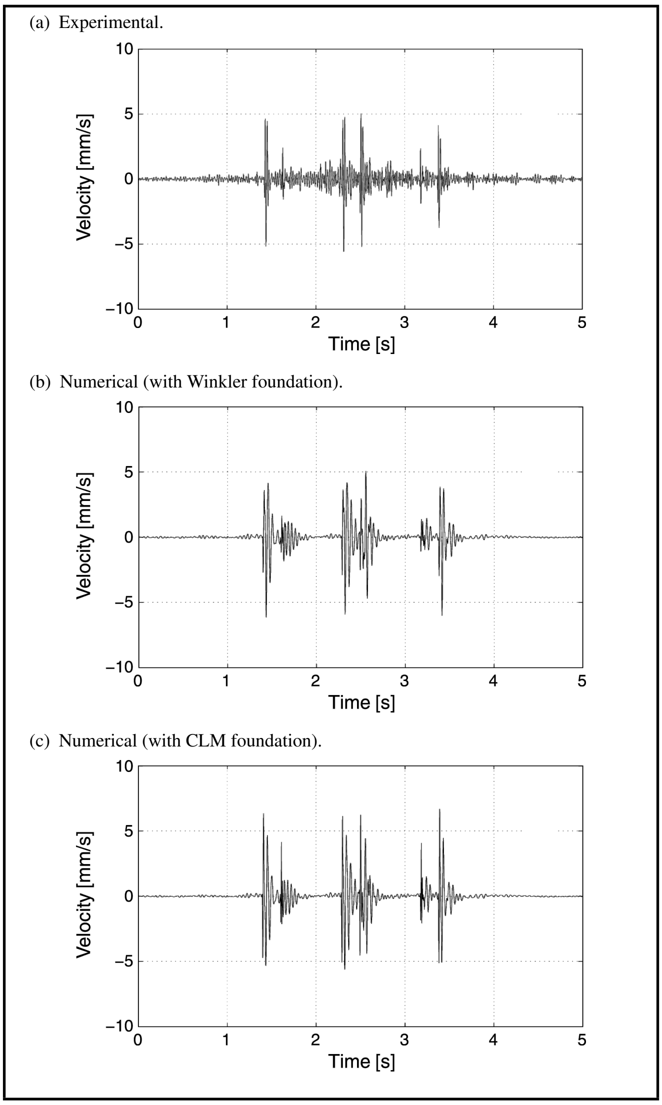


Figure 11. The vertical ground velocity at $2\,\mathrm{m}$ from the track during the passing of the Tram T2008 at the speed $v_0 = 30\,\mathrm{km/h}$ (local defect).

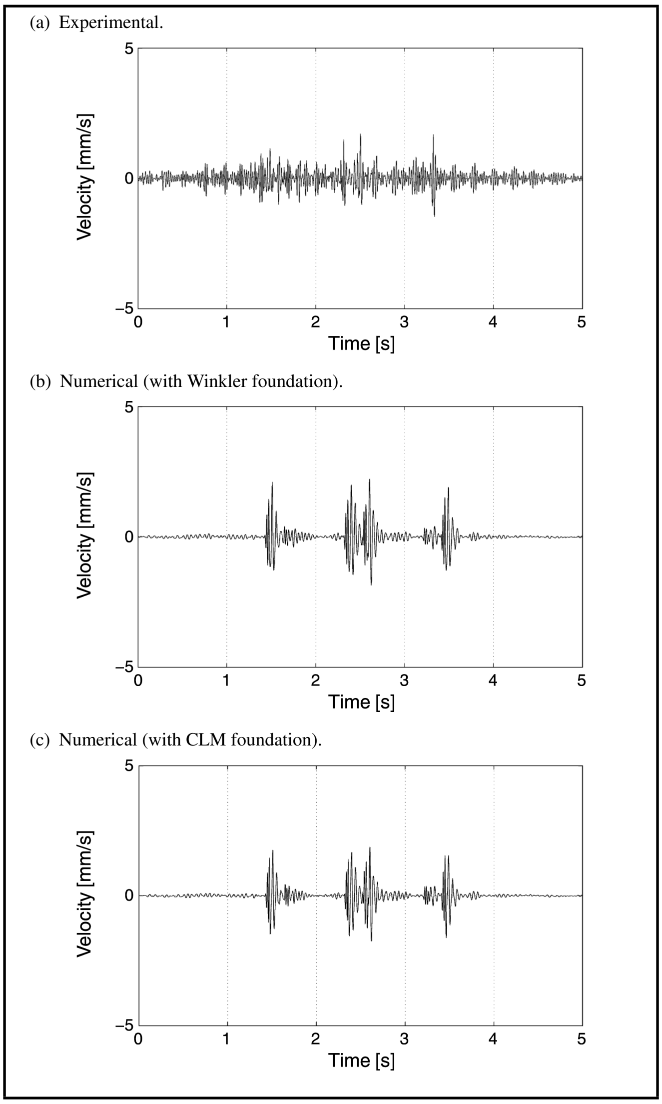


Figure 12. The vertical ground velocity at $8\,\mathrm{m}$ from the track during the passing of the Tram T2008 at the speed $v_0 = 30\,\mathrm{km/h}$ (local defect).

for soil/structure models and impact-based modal analysis gets around this problem with the help of the discrete Fourier transform. Calculated transfer functions of the ground and first floors at various locations are shown in Fig. (14), which confirms the results obtained in Fig. (13) for the upper floor vibrations. The ground floor does not have significant resonances in the analysed frequency range and the first floor presents two well-marked peaks, around 15 and 25 Hz, which can be associated with bending modes found by the modal analysis. It can be concluded that a modal analysis of the building, considering a fixed foundation, is sufficient to estimate the upper floor modes.

3.5. Structural Response

This section will try to numerically evaluate the effects of railway vibrations on a typical private house in the vicinity of the track. Since it has been validated in free-field, the proposed model can be used to evaluate the effects of the tram passing near the building. The latter is placed at $4\,\mathrm{m}$ from the track (distance from the front wall to the exterior rail) with the large front wall parallel to the track, which corresponds to a realistic situation often encountered in an urban area. The T2000 Tramway is simulated in a straight line considering a local rail defect, in front of the building.

Figure (15) presents the vertical velocity at the ground and upper floors, with the addition of the equivalent free-field velocity (in red dashed lines). The reference positions are located in the middle of the building width, at three-quarters along the length (location with cross markers in Fig. (14)). Besides the time history, the frequency content and the time-averaged signal are depicted. The latter is defined by the time weighted signal $KB_F(t)$.[22] The impact of each wheel on the local defect is emphasized on the figures, each axle crossing the defect at $t = 1.4\,\mathrm{s}$, $t = 1.6\,\mathrm{s}$, $t = 2.3\,\mathrm{s}$, $t = 2.5\,\mathrm{s}$, $t = 3.2\,\mathrm{s}$, and $t = 3.4\,\mathrm{s}$.

By analysing these results, some important remarks can be made:

- The amplitudes of displayed vibration in ground and upper floors signals are similar, with some discrepancies that are more easily observed in Fig. (16), which represents the seismic wave propagation along a plane perpendicular to the track, and in front of the defect. A decrease in amplitude is shown when the building is taken into account. Frequency contents of free-field and structural responses are also comparable at the ground level, with a maximum between 22 and 24 Hz, corresponding to the bogie pitch

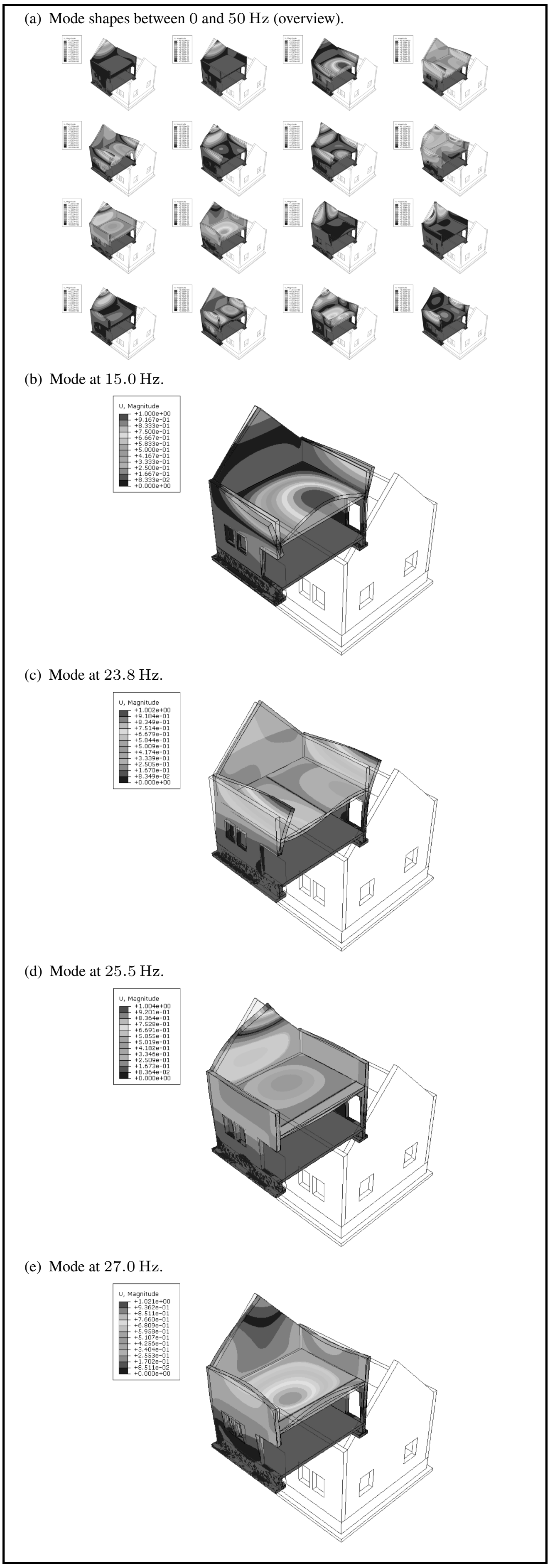


Figure 13. A modal analysis of the building (with fixed boundary conditions).

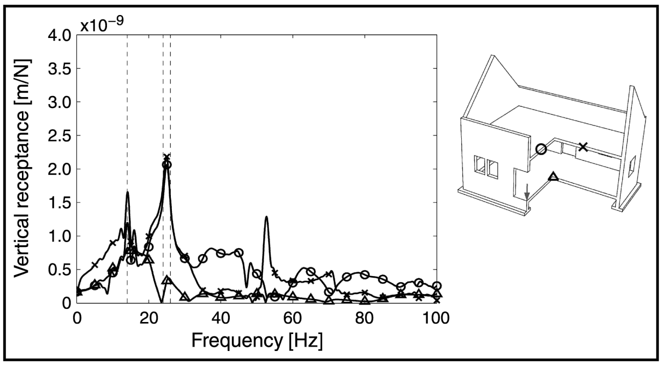


Figure 14. The transfer functions of the building (excitation at the foundation of house).

modes of the vehicle (excitation signature). Notice that no notable difference in amplitude is detected between the ground and the first floor vibrations.

- The main observation, however, is the difference in the frequency content between the ground and the first floor vibrations. The bending modes, at $15\,\mathrm{Hz}$ and $27\,\mathrm{Hz}$, clearly dominate the signal, with a complete disappearance of the excitation frequency due to the mode shapes around this frequency. Although each load effect can be distinguished at the ground level, that is less obvious on the first floor.

4. CONCLUSION

This paper presents an overview of the potential of the FE approach, with an accurate prediction of railway excitation, to evaluate the ground-borne vibrations and the building structure's dynamic response due to railway traffic. In order to avoid complicated and heavy models for vehicle/track/soil simulation, a discrete and condensed form of the foundation has been developed, including the coupling through the track contact area. Based on the Lysmer's analogue foundation, spring and damper elements have been included for the purpose of coupling between foundations.

Combined with a two-stages approach, the prediction of railway-induced ground vibrations can be done, through an example issued from the tramway network of Belgium. Frequency analysis on the excitation and the receiver has been performed, in order to reveal the vibration modes dominating the free-field and structural responses. Particularly, the seismic wave propagation is different between the two cases. A complete vehicle/track/soil/structure model is thus necessary to take into account the local coupling between the different substructures. This kind of prediction model, based on the finite element approach and thoroughly validated in free-field case, is presented as a useful tool for predicting the soil/structure dynamics subject to external loads.

APPENDIX A. DETAILS OF THE MEASURED AND CALCULATED PARAMETERS: VEHICLE, TRACK, SOIL, AND BUILDING

The Tram T2000 presented in this paper has the following dynamic properties:

- front and rear carbody mass $m_c = 7580\,\mathrm{kg}$;

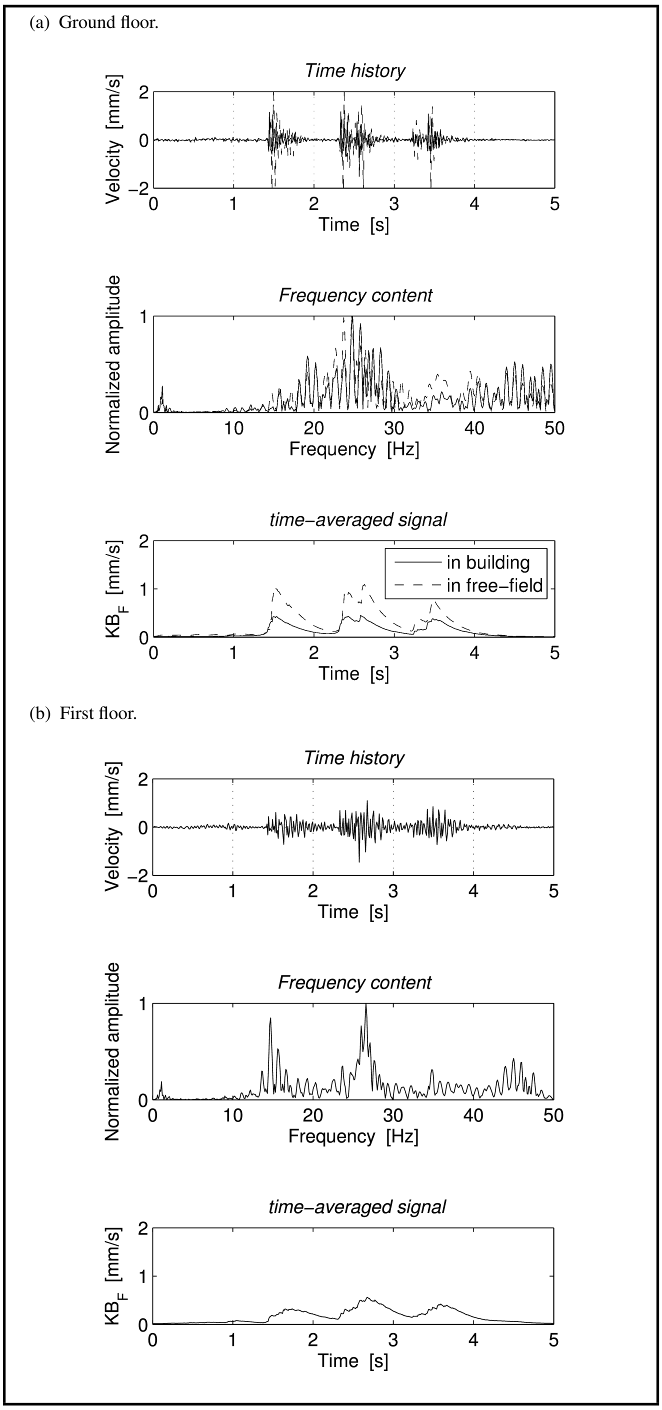


Figure 15. The time history, spectral content and time-averaged signal of building vibrations, in the case of a vehicle speed of 30 km/h moving along a track with a local defect.

- central carbody mass $m_{cc} = 2600\,\mathrm{kg}$;
- bogie mass $m_b = 1800\,\mathrm{kg}$ and pitch inertia $I_b = 300\,\mathrm{kg\cdot m^2}$;
- independent motor wheel mass $m_m = 945\,\mathrm{kg}$, with a tread of $m_t = 80\,\mathrm{kg}$, resilient material of stiffness $k_t = 145\,\mathrm{MN/m}$, and damping $d_t = 3\,\mathrm{kNs/m}$;
- trailer wheel mass $m_d = 160\,\mathrm{kg}$;
- primary suspension (trailer wheels) of stiffness $k_d = 5.88\,\mathrm{MN/m}$ and damping $d_d = 6\,\mathrm{kNs/m}$;

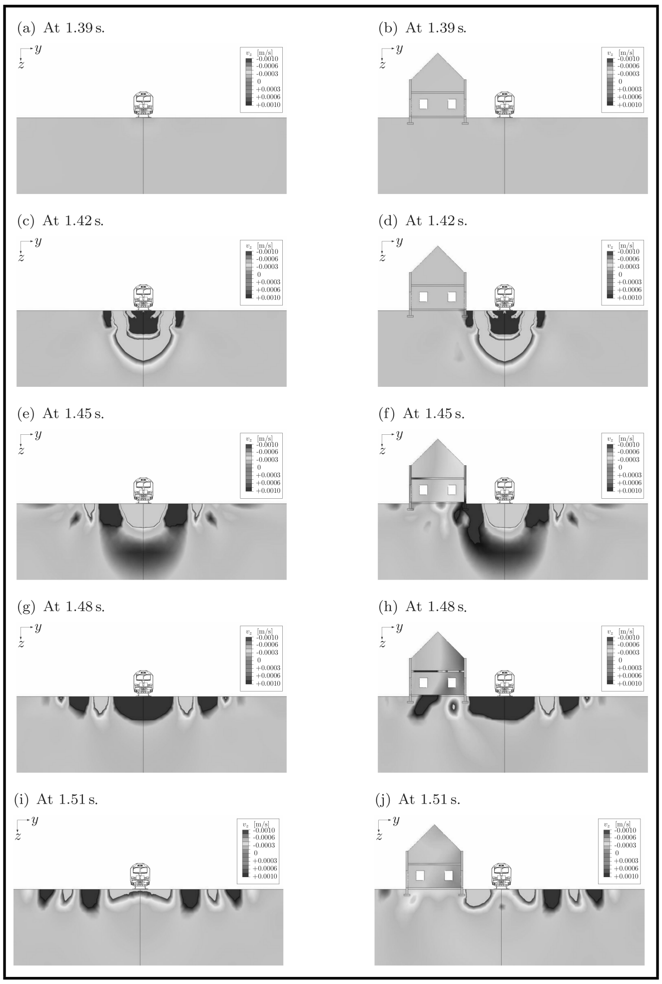


Figure 16. The propagation of the free-field (left) and structural response (right) vertical component of the soil vibration waves, in the case of a vehicle speed of 30 km/h moving along a track with a local defect.

Table 2. Track properties.

Rail flexural stiffness	$E_r I_r$	$4.17\,\mathrm{MNm^2}$
Rail mass per length	$\rho_r A_r$	$54\,\mathrm{kg/m}$
Sleeper spacing	L	$0.72\,\mathrm{m}$
Railpad stiffness	k_p	$90\,\mathrm{MN/m}$
——— damping	d_p	$30\,\mathrm{kNs/m}$
Ballast stiffness	k_b	$32\,\mathrm{MN/m}$
——— damping	d_b	$52\,\mathrm{kNs/m}$

- primary suspension (motor wheels) of stiffness $k_m = 44\,\mathrm{MN/m}$ and damping $d_m = 18\,\mathrm{kNs/m}$;
- secondary suspension of stiffness $k_2 = 960\,\mathrm{kN/m}$ and damping $d_2 = 56.25\,\mathrm{kNs/m}$.

The parameters of the track and the foundation are presented in Table 2. The CLM model parameters associated with a half track are: $m_f = 2502\,\mathrm{kg}$, $k_f = 30\,\mathrm{MN/m}$, $k_c = 41\,\mathrm{MN/m}$, $d_f = 150\,\mathrm{kN/m}$, and $d_c = -23\,\mathrm{kN/m}$ (see Fig. (3)).

The soil is represented by visco-elastic behaviour, according to a 6-layer configuration proposed by Degrande et al.[23] Values are presented in Table 3, and a progressive soil rigidity with depth is assumed.

The building is a two-story structure with a rectangular plan and an embedded concrete box foundation (depth $0.85\,\mathrm{m}$), and it is representative of typical houses in Brussels. Main dimensions (length × width × height) are $10\,\mathrm{m} \times 7\,\mathrm{m} \times 5\,\mathrm{m}$ with the following properties:

Table 3. Soil characteristics and layering.

	Young's Modulus	Density	Poisson's ratio	Viscous damping	Depth
	MPa	kg/m^3	—	s	—
Layer 1	61	1876	0.13	0.0004	1.2
Layer 2	84	1876	0.13	0.0004	1.8
Layer 3	287	1876	0.13	0.0004	1.0
Layer 4	373	1876	0.27	0.0004	1.0
Layer 5	450	1876	0.33	0.0004	1.0
Halfspace	465	1992	0.48	0.0004	—

- Walls are in masonry (Young's modulus $10\,\mathrm{GPa}$, shear modulus $4.2\,\mathrm{GPa}$ and density $1800\,\mathrm{kg/m^3}$), and have a constant thickness of $0.25\,\mathrm{m}$.

- Foundations as well as floors are in concrete (Young's modulus $20\,\mathrm{GPa}$, shear modulus $8.3\,\mathrm{GPa}$, and density $2400\,\mathrm{kg/m^3}$). The floors thickness is equal to $0.20\,\mathrm{m}$.

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