

Deterioration of Track Geometry in Ballasted High Speed Line: Modeling Approach and Parametric Study

A. Martin, O. Chupin & J.-M. Piau

LUNAM Université, IFSTTAR, Bouguenais, France

P.-Y. Hicher

LUNAM Université, Ecole Centrale de Nantes, UMR CNRS GeM, Nantes, France

ABSTRACT: In the context of environmental sustainability and increasing traffic volume, the emergence and modernization of public transportation are encouraged. As regards to High Speed Line (HSL), this leads to an increase of operating speeds which seems to be responsible for unusual fast evolving geometrical disorders observed in ballasted tracks. To tackle this problem, a study is launched dealing with the understanding of such disorders and the analysis of the influence of some structural parameters. For this purpose, we have developed a numerical program based on continuum mechanics that consists in computing the dynamic response of a railway structure under loads moving at constant speed. The developed method relies on the adaptation of the quasi-stationary technique to railway tracks. Moreover it allows taking into account the viscoelastic behavior of possible bituminous layers through the Huet-Sayegh model for asphalt materials. Using this developed numerical tool, the impact of the train speed on the ballast layer is studied by looking at the evolution of the vertical acceleration within this layer. A parametric study is then performed to determine which parameters make it possible to mitigate the computed accelerations. The considered parameters are the pad stiffness, the moment of inertia of the rail and the contrast of layer moduli. The results of the numerical simulations are discussed in the aim of proposing realistic solutions to minimize geometrical disorders in the ballast layer.

KEY WORDS: High-speed rail, ballast, geometrical disorders, parametric study, vertical accelerations.

1 INTRODUCTION

Fast evolving disorders were recently observed in ballasted High-Speed Lines (HSL) for which the operating speed was increased above 75 m/s (i.e. 270 km/h). It is believed that such disorders are related in part to high values of acceleration within the ballast layer. Based on numerical simulations, Chupin and Piau (2011a, 2011b) have shown in particular that some regions in the ballast layer are subjected to significant downward accelerations combined to small vertical stress representative of low confinement of this granular layer. It is believed that this combination is particularly detrimental to the ballast layer and may promote the onset of geometrical disorders. Following this scenario, one way to mitigate such disorders would be to reduce the acceleration within the ballast layer. In this context and based on numerical simulations of the dynamic response of the railway structure, we first analyze in this paper the

effect of the train speed on the computed acceleration within ballast. Then, we present a parametric study whose aim is to evaluate the impact of some structural components of the railway on acceleration. First of all, the numerical program utilized to compute the dynamic response of the railway structure is briefly described.

2 DESCRIPTION OF THE NUMERICAL PROGRAM USED TO COMPUTE THE RESPONSE OF HSL

In this paper, the dynamic response of railway structures is computed using the numerical program presented in Chupin and Piau (2011a). The latter relies on the utilization of the ViscoRoute© 2.0 numerical program (Duhamel et al., 2005; Chabot et al., 2010; Chupin et al., 2010) which was initially dedicated to compute the response of pavement structures to moving loads. The assumptions considered in ViscoRoute© 2.0 enable the elastodynamic problem to be treated according to a quasi-stationary approach and to be solved using a semi-analytical method. In ViscoRoute© 2.0, the pavement structure is modeled as a semi-infinite layered medium whose layers are either linear elastic or viscoelastic according to the Huet-Sayegh model (Huet, 1963; Sayegh, 1965; Huet, 1999), which is particularly well suited for asphalt materials.

In the case of railways and contrary to pavements, the loading applied on the structure (or trackbed, see Figures 1 and 2) arises from the load transfer across the rail/sleeper system under a passing train. To simplify, the stress distribution resulting from this load transfer is supposed here to be uniform under each block of the considered bi-block sleepers. Also assuming a constant speed of the train, it can be written under the following generic form:

$$\sigma_{zz}(x, y, t) = [H(y + a) - H(y - a)]p(x, t) \quad (1)$$

with

$$p(x, t) = \sum_{n=-\infty}^{n=+\infty} [H(x - nl + b) - H(x - nl - b)]f(nl - Vt) \quad (2)$$

in which n is the sleeper number, $2a$ and $2b$ are the width and the length of a sleeper block, l is the center-to-center distance between two sleepers and H is the Heaviside step function (see Figure 1). $f(nl - Vt)$ is a master curve that defines the amplitude of the stress distribution and that takes account of the location of the train moving at speed V . The sole function f makes it possible to determine $p(x, t)$ at any time t (see Figure 2). The master curve is determined by decoupling the initial problem in two subsystems which are the rail/sleeper system and the trackbed, respectively. In the first subsystem the rails and the sleeper blocks are modeled by Euler-Bernoulli beams and springs that ensure the mechanical connection between the rails and the structure. The latter is modeled as a semi-infinite layered medium. The dynamic response of the global system to loads applied on the rails is computed using an iterative technique that yields the stress distribution at the interface between the subsystems and subsequently the master curve.

Now, the stress distribution defined by Eq.(2) varies with time since it depends on the location of the train wheels moving on the rails. Consequently, it is not straightforwardly compatible with the quasi-stationary assumption and cannot represent as such the moving loads taken as an input of ViscoRoute© 2.0 for the computation of the dynamic response of the structure. So to enable the transposition of ViscoRoute© 2.0 to railways, Chupin and Piau (2011a) have developed a method that consists in decomposing $p(x, t)$ into loading waves

moving at different positive or negative speeds. These loading waves are continuous functions constant with time. Each of them can thus be used as an input of a quasi-stationary ViscoRoute© 2.0 calculation. The recombination of the loading waves yields the loading function $p(x,t)$ and the mechanical response of the railway structure is obtained by recombination of the individual responses to each loading wave (outputs of the ViscoRoute© 2.0 calculations). This method has been implemented in a numerical script whose advantage is that it allows the dynamic response of the railway structure to be computed in short duration times, what is convenient for parametric studies. This script is used further in this paper to compute vertical accelerations within the ballast layer.

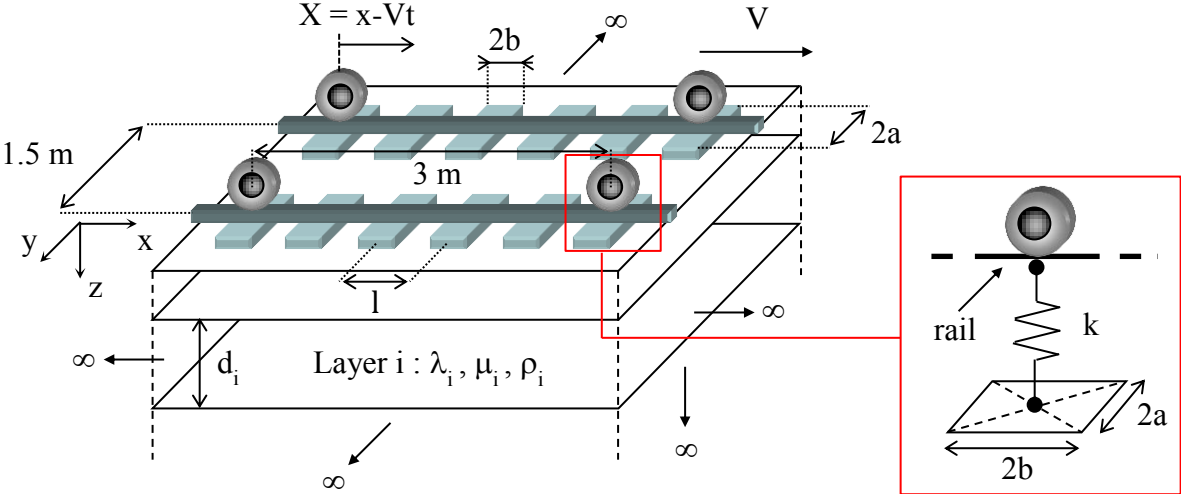


Figure 1: Railway track system under consideration (from Chupin and Piau, 2011a).

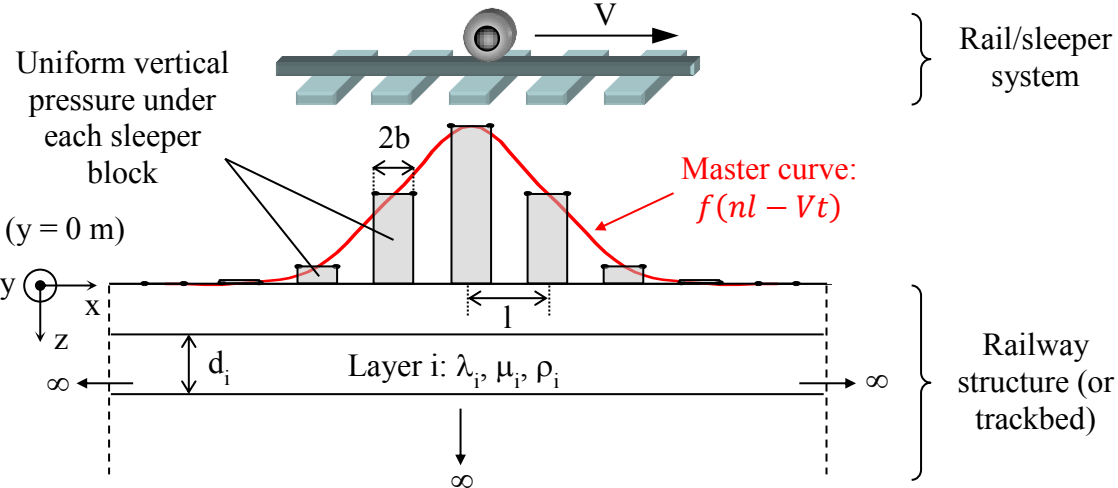


Figure 2: Modeling of the load distribution at the surface of the structure at a given time t (representation for one wheel applied on the rail) (from Chupin and Piau, 2011a).

3 DYNAMIC RESPONSE OF A CLASSIC HSL WITH BALLAST BED AND SENSITIVITY ANALYSIS

In this section, a classic HSL with ballast bed is analyzed and a parametric study of the vertical acceleration, γ_z , in the ballast layer is performed. We define a reference case for which the influence of the train speed on γ_z is evaluated and then the parametric study is run by varying some quantities (one at a time) starting from this reference case.

3.1 Description of the reference case and influence of the train speed on γ_z

The structure of the reference case is composed of three elastic layers whose properties are summarized in Table 1. Note the Young modulus of the ballast layer is chosen such that no tensile stress develops in this granular layer. The dimensions of the sleeper blocks are $2a = 0.8 \text{ m}$, $2b = 0.3 \text{ m}$, and the center-to-center distance between two sleepers is $l = 0.6 \text{ m}$ (see Figure 1). The rails are modeled by Euler-Bernoulli beams of Young's modulus equal to $210 \times 10^3 \text{ MPa}$ and of moment of inertia (I_{rail}) equal to $3 \times 10^{-5} \text{ m}^4$. The stiffness of the springs that ensure the connection between the rails and the structure is set to $k_{spr} = 50 \text{ MN/m}$. The reference load applied on the rails is a bogie with 4 wheels, each of which is represented by a point force $F = 80 \text{ kN}$ applied in the vertical direction, and moving at a speed of $V = 75 \text{ m/s}$.

First, we study for the reference case the effect of speed on γ_z computed at mid-depth of the ballast layer (i.e. in $z = 0.15 \text{ m}$). The results are presented under the form of horizontal profiles in the x-direction, obtained at a given time corresponding to F located right above sleeper centers, and for a transversal position matching with one of the rail axis ($y = 0$). These are plotted in Figure 3 for three speeds which are 75, 95 and 115 m/s .

Table 1: Properties of the layered medium representing the railway structure.

	$\rho \text{ (kg/m}^3\text{)}$	$E \text{ (MPa)}$	ν	Thickness (m)
Ballast	1800	150	0.4	0.3
Sub-ballast layer	1800	120	0.4	0.7
Soil	1800	100	0.4	∞

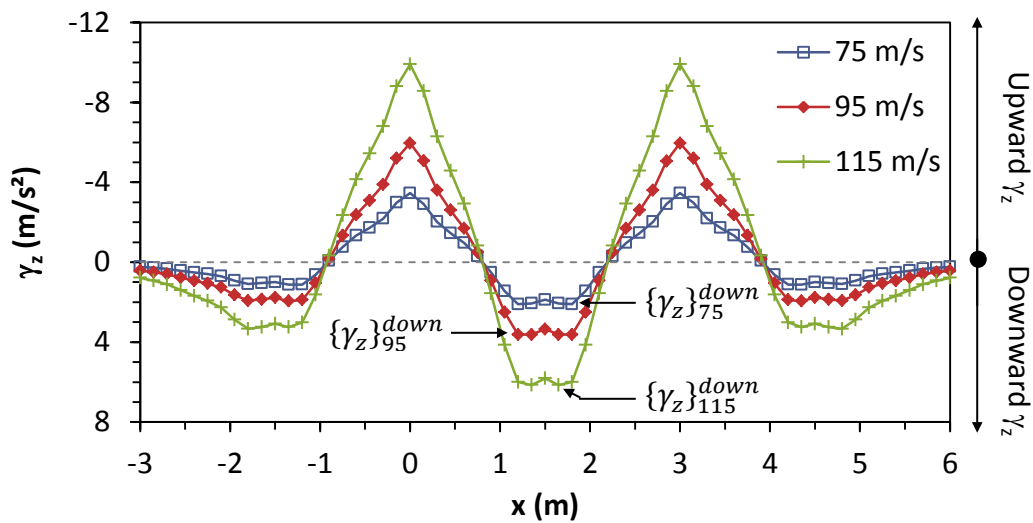


Figure 3: Vertical accelerations computed at mid-depth of the ballast layer ($z = 0.15 \text{ m}$, $y = 0$) for speeds equal to 75, 95 and 115 m/s (i.e. 270, 342 and 414 km/h , respectively).

The reference profile obtained for $V = 75 \text{ m/s}$ is shown with square symbols in Figure 3. It shows vertical accelerations oriented upward under the bogie axles ($x = 0$ and $x = 3 \text{ m}$) and in that vicinity. Downward accelerations are found elsewhere, i.e. between the two bogie axles as well as ahead and behind the front and rear axles, respectively. We notice that γ_z is higher in the upward than in the downward direction. Additionally, although not presented herein, it is shown in Chupin and Piau (2011a) that in the regions where γ_z is oriented downward the compressive stresses are quite small. The combination of small stresses and significant downward γ_z is suspected to be damaging for the ballast layer, and possibly more than higher upward γ_z associated to high compressive σ_{zz} as it can be encountered in the regions under the bogie axles.

Table 2: Ratios between the maximum downward γ_z computed for different speeds and $V = 75 \text{ m/s}$ (reference case), and comparison with the speed square ratios.

$V \text{ m/s}$	$\{\gamma_z\}_V^{\text{down}} \text{ (m/s}^2\text{)}$	$\{\gamma_z\}_V^{\text{down}} / \{\gamma_z\}_{75}^{\text{down}}$	$(V/75)^2$
75	2.10	1	1
95	3.62	1.72	1.60
115	6.15	2.93	2.35

Now looking at the influence of speed on γ_z , we notice that the profile shapes are similar for the three curves plotted in Figure 3 but also that the ratio between the magnitude of γ_z computed for two different speeds is relatively close to that of the speed square values (see Table 2). The difference between these ratios is due to inertia effects in the structure and thus increases with speed.

3.2 Parametric study of the vertical acceleration in the ballast layer

Now based on field experience, we assume that γ_z computed for the reference case ($V = 75 \text{ m/s}$) yields a safe situation with regards to fast-evolving disorders in the ballast layer. Then, the aim of the parametric study is to highlight some structural components of the railway having a significant impact on γ_z and which could be used further to bring back accelerations obtained for higher speeds at the level of those of the reference case. The parameters considered in the present study are the stiffness (k_{spr}) of the mechanical connection between the rails and the trackbed (stiffness of the springs in Figure 1), the moment of inertia of the rails (I_{rail}) and the Young modulus of the sub-ballast layer ($E_{sub-ballast}$).

The same characteristic profiles ($z = 0.15 \text{ m}$, $y = 0$, F in $x = 0$ and 3 m) as in section 3.1 are plotted below for different values of the varied parameters and for a speed of 75 m/s .

3.2.1 Influence of the rail/trackbed contact stiffness

In Figure 4, the vertical accelerations arise from the computation of the dynamic response of the reference case for which the spring stiffness (k_{spr}) is varied among the following values: 10, 50 and 100 MN/m . The reference case corresponding to 50 MN/m is plotted with square symbols.

As shown in Figure 4, a decrease of the spring stiffness yields a decrease of the magnitude of the vertical acceleration in both directions. This is explained in part by the fact that as the spring stiffness decreases the resulting force applied on the rails is distributed over an increasing number of sleepers, reducing in that way the maximum pressure on the most loaded sleepers (located under the wheel loads).

Consequently, a possible way to mitigate γ_z in real railway structures would be to soften the mechanical connection between the rails and the structure by adding for example a flexible mat under the sleepers or between the rails and the sleepers.

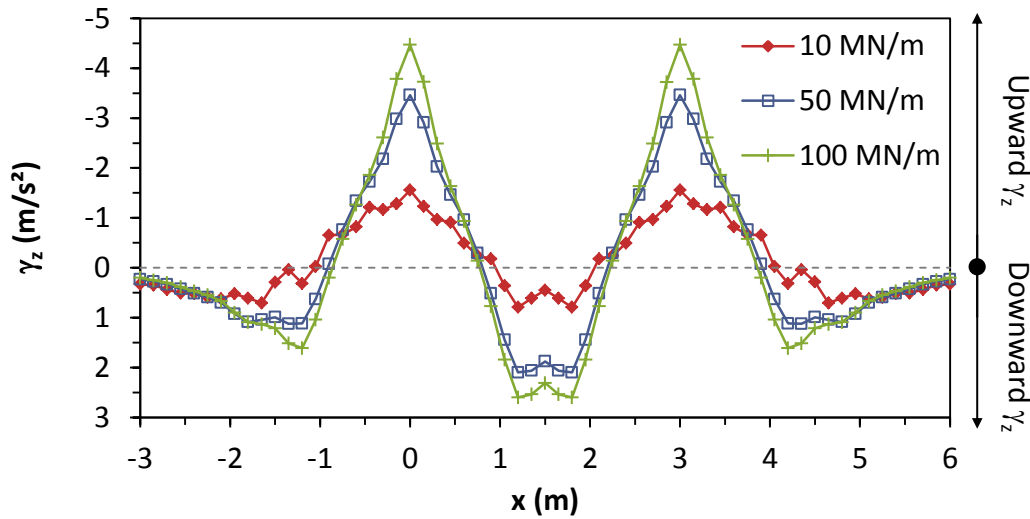


Figure 4: Vertical accelerations computed at mid-depth of the ballast layer for values of the spring stiffness (k_{spr}) equal to 10, 50 and 100 MN/m ($z = 0.15$ m, $y = 0$, $V = 75$ m/s).

3.2.2 Influence of the moment of inertia of the rail

In this section, the moment of inertia of the rail (I_{rail}) is varied keeping all the other parameters equal to those of the reference case. The tested values for the moment of inertia are: 1×10^{-5} , 3×10^{-5} (nominal case) and 5×10^{-5} m^4 . Figure 5 shows the computed vertical acceleration at mid-depth of the ballast layer for the different tested values. Again the reference case corresponding to $I_{rail} = 3 \times 10^{-5}$ m^4 is plotted with square symbols.

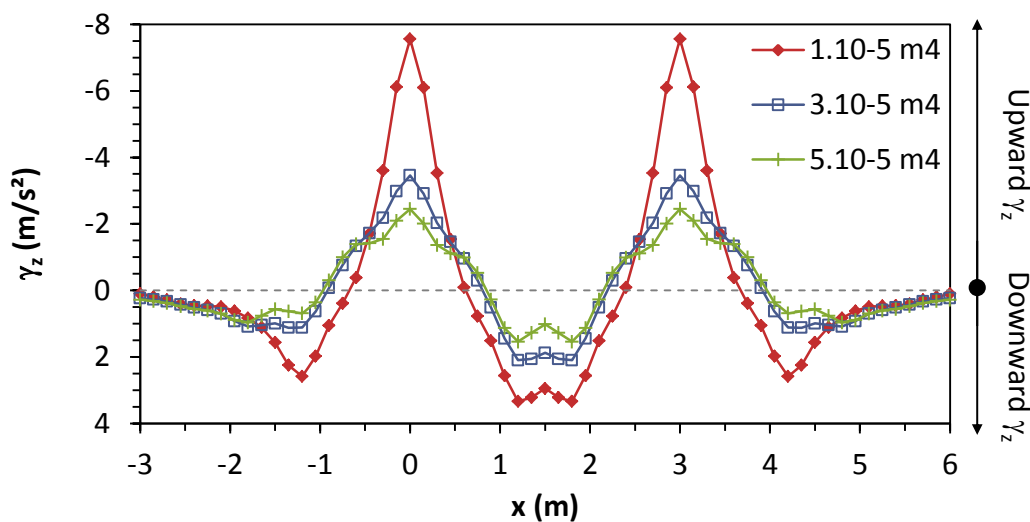


Figure 5: Vertical accelerations computed at mid-depth of the ballast layer for values of the rail moment of inertia (I_{rail}) equal to 1×10^{-5} , 3×10^{-5} and 5×10^{-5} m^4 ($z = 0.15$ m, $y = 0$, $V = 75$ m/s).

It is noticed that γ_z decreases in magnitude in both directions as the moment of inertia of the rails increases. High values of I_{rail} contribute to distribute over more sleepers the resulting force applied on the rails and to reduce the maximum pressure applied at the surface of the structure.

3.2.3 Influence of the Young modulus of the sub-ballast layer

In this section, the parameter which is varied with regards to the reference case is the Young modulus of the sub-ballast layer. The tested values are $E_{sub-ballast} = 120, 250, 500, 1000,$ and 5000 MPa . High values of the Young modulus could correspond for example to a sub-ballast layer made up of a treated material. Note that the tested values given above enable to respect the aforementioned no-tensile-stress criterion in the ballast layer. Figure 6 shows the horizontal profile of γ_z for the different tested values. It is observed that the magnitude of γ_z decreases with the increase of $E_{sub-ballast}$. The maximum downward values of γ_z can be divided by about 3 as compared to the reference case when $E_{sub-ballast}$ reaches values of 1000 MPa and by about 5 when $E_{sub-ballast}$ is equal to 5000 MPa . Improving the sub-ballast material to obtain a stiffer layer seems to be another way to reduce γ_z in the ballast layer. Nonetheless, the impact of such improvement on the resulting stress in the sub-ballast layer and subsequently the fatigue damage of it (long-term behavior) would have to be studied.

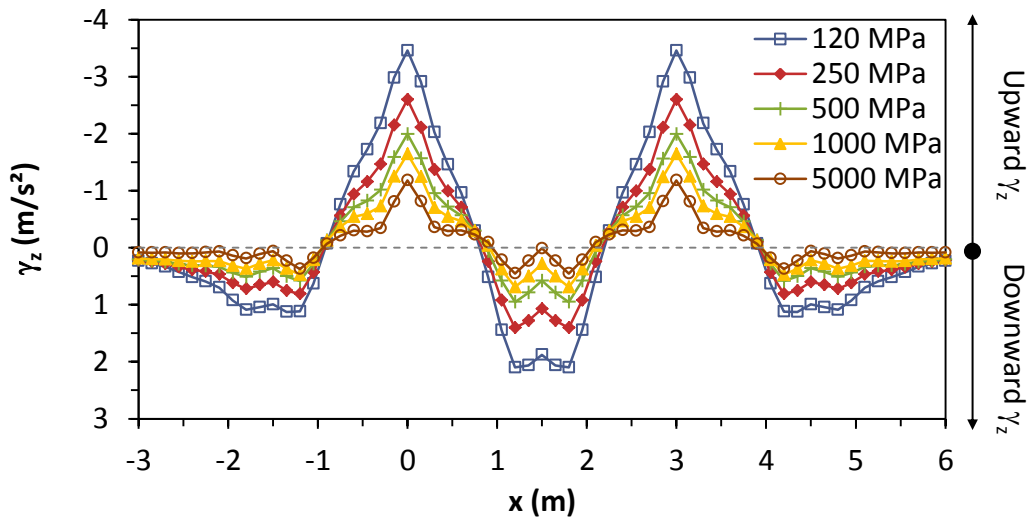


Figure 6: Vertical accelerations computed at mid-depth of the ballast layer for values of the Young modulus of the sub-ballast layer ($E_{sub-ballast}$) equal to 120, 250, 500, 1000 and 5000 MPa ($z = 0.15 \text{ m}$, $y = 0$, $V = 75 \text{ m/s}$).

3.2.4 Summary of the results of the sensitivity analysis

Table 3 presents a summary of some results of the parametric study. It gives the ratios between the maximum downward γ_z obtained for the different values of the varied parameters and for the reference case. These ratios can be evaluated by comparison with the square speed ratios $(V/75)^2$.

Table 3: Ratios between the maximum downward γ_z obtained in the parametric study and the reference case.

Parameter	k_{spr} (MN/m)			I_{rail} ($\times 10^{-5} m^4$)		
Value	10	50	100	1	3	5
Ratio	0.38	1	1.24	1.59	1	0.73
Parameter	$E_{sub-ballast}$					
Value (MPa)	120	250	500	1000	5000	
Ratio	1	0.67	0.45	0.33	0.21	

4 CONCLUSIONS

In this study, we have computed the dynamic response of railway structures modeled as semi-infinite layered media and subjected to train loads. A numerical program developed by the authors was used and emphasis was placed on the vertical acceleration (γ_z) within the ballast layer. This quantity is believed to be critical in the analysis of the fast evolving disorders observed in the ballast of HSL. Under the assumptions made, the effect on γ_z of the train speed and of some structural parameters was quantified. In particular, we have shown that decreasing the stiffness of the mechanical connection between the rails and the track construction, increasing the moment of inertia of the rails or the Young modulus of the sub-ballast layer yields a decrease of γ_z . In the future, this parametric study could help make γ_z go under some threshold value that might be damaging for the track geometry.

REFERENCES

- Chabot, A., Chupin, O., Deloffre, L. and Duhamel, D., 2010. *ViscoRoute 2.0: a tool for the simulation of moving load effects on asphalt pavement*. Road Materials and Pavement Design, 11(2), pp.227–250.
- Chupin, O., Chabot, A., Piau, J.M. and Duhamel, D., 2010. *Influence of sliding interfaces on the response of a layered viscoelastic medium under a moving load*. International Journal of Solids and Structures., 47(25-26), pp.3435–3446.
- Chupin, O. and Piau, J.M., 2011a. *Modeling of the dynamic response of ballast in high-speed train structures*. In: Proceedings of the 8th International Conference on Structural Dynamics. EUROLYN 2011. Leuven, Belgium, pp. 712–718.
- Chupin, O. and Piau, J.M., 2011b. *Modélisation de la réponse dynamique d’une structure ferroviaire multicouche sous chargement roulant*. In: 20ème Congrès Français de Mécanique. CFM 2011. Besançon, France.
- Duhamel, D., Chabot, A., Tamagny, P. and Harfouche, L., 2005. “*ViscoRoute*”: *Viscoelastic modeling for asphalt pavements*. Bulletin des Laboratoires des Ponts et Chaussées, (258-259), pp.89–103.
- Huet, C., 1999. *Coupled size and boundary-condition effects in viscoelastic heterogeneous and composite bodies*. Mechanics of Materials, 31(12), pp.787–829.
- Huet, C., 1963. *Etude par une méthode d’impédance du comportement viscoélastique des matériaux hydrocarbonés*. PhD Thesis. Université de Paris, France.
- Sayegh, G., 1965. *Contribution à l’étude des propriétés viscoélastiques des bitumes purs et des bétons bitumineux*. PhD Thesis. Faculté des Sciences de Paris, France.