Environmental impact caused by high speed train vibrations

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ABSTRACT: In recent years the high speed railway connections have given more evidence to damage and disturbance caused by vibrations to the environment: buildings, factories, people. Vibrations produced by traveling trains are the result of the dynamic interaction among the train, the track and the supporting soil. A simplified model is proposed to solve the SSI problem. The method has been validated by comparing the results with both an independent theoretical method and some experimental data measured at a site available in the literature. The method has been applied to predict the dynamic forces and the wave motion under the track on the free surface of the ground for the ETR 500 Y Italian high speed train, within reasonable ranges of the train speed and of the soil characteristics. The results represent a simple but pragmatic tool to be used for preliminary design and for the evaluation of the environmental impact caused by high speed train vibrations.

Key words: train vibrations, dynamic SSI, environmental impact, soil and structural dynamics

1. INTRODUCTION

Environmental impact caused by vibrations generated by high speed trains is of major concern in recent years, since technological improvements in railway connections have allowed for very high speed to be reached.
Vibrations induced by traveling trains may cause serious damage to the economical performance of factories, which are equipped with sensible industrial machines or they may disturb people living or operating in buildings placed near a railway or a subway (Bernal D. et al. 2003). Vibrations generated by trains can be considered the result of a particular case of SSI (soil structure interaction) under dynamic conditions. In the following a simple but sufficiently adequate analytical approach is presented, to predict the forces and the wave motion transmitted by the train to the soil through the track system.

2. SSI MODEL TO PREDICT VIBRATIONS

The whole system consists of the following principal sub-structures: the train, the track and the soil (see figure 1).

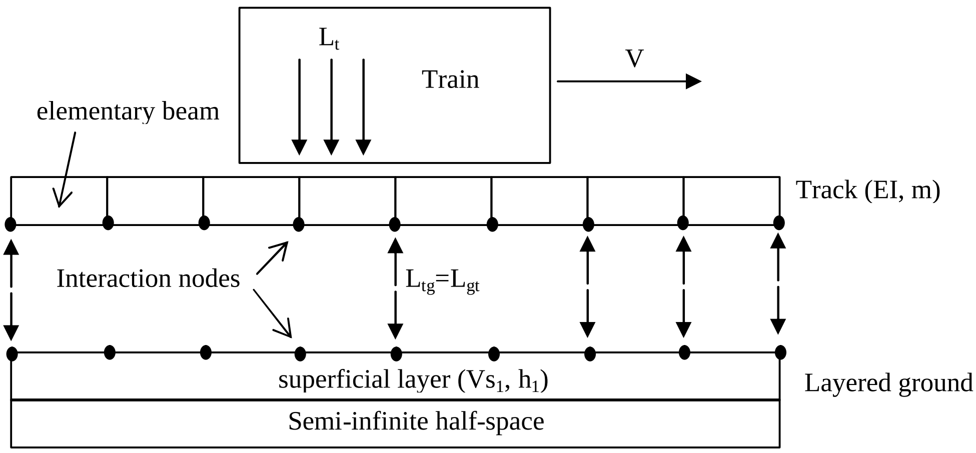

Figure 1. Schematic representation of the SSI model.

2.1. Train model

The train has been simplified to a series of vertical loads Lt, which are placed according to the geometry and the composition of the train (locomotives, bogies, wheels, axles) and move at a constant speed v on the track.

In the following the super-fast (maximum allowed speed V_{max}=300km/h) Italian train ETR 500Y has been considered. This train is made of two locomotives plus ten bogies with the axles of the wheels positioned according to the loading scheme shown in figure 2.

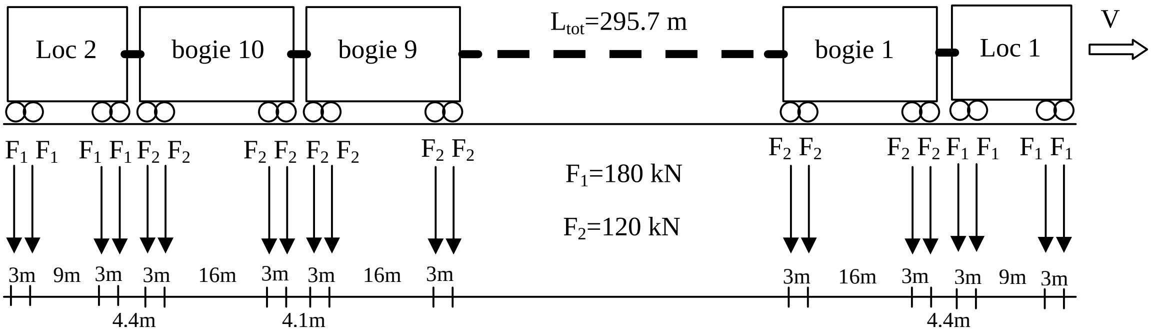

Figure 2. Schematic representation of the loads transmitted by the axles of the wheels of the super-fast train ETR 500 Y .

2.2. Track model

The track is made by the following sub-structures: the rails, the sleepers and the ballast. In some cases the ballast may be substituted by a stiff basement, generally a concrete slab foundation.
Usually the track is modelled as an elastic Euler-Bernoulli beam, which is constituted by an infinite series of elementary beams with a flexural stiffness EI and a linear mass m. The total dynamic stiffness matrix Kt of the track is obtained by assembling the dynamic stiffness matrices of all the elementary beams (sub-index i) (Clough and Penzien 1994, Kaynia et al. 2000):

$$K_t^i = K^i - w^2 M^i \quad (1)$$

where K^i is the static stiffness matrix and M^i is the consistent mass matrix.

2.3. Soil model

Generally two types of approach are followed to model the soil and its connection with the track (i.e the rail plus the sleepers and the ballast and /or a stiff basement). In the first approach the track rests on a soil, which is idealized as a series of independent Winkler springs. This method offers the advantage of modelling soil non linear behaviour, but does not consider frequency dependent damping of the soil, which gives a relevant contribution to attenuate the system response at train speeds, that cause resonance conditions. Also spatial continuity of the ground is not allowed by the independent Winkler springs. The second approach consists of modelling the track as an elastic Euler-Bernoulli beam, which is linked to the soil through a discrete series of nodal points. The soil is modelled as a continuous horizontally layered half-space, dynamically characterized in terms of frequency dependent stiffness and damping (Roma V. 2001). In this paper the second approach has been adopted.
The dynamic stiffness matrix Kg(ω-r) in the frequency-space domain of the layered ground corresponding to the interaction nodes can be obtained by inverting the matrix Δ of the Green's functions δij, which give the ground displacement at node i, caused by a steady-state harmonic unit load at node j.

$$K_g = \Delta^{-1} \quad (2)$$

The Green's functions δij can be calculated by applying inverse Hankel transforms to the components of the dynamic stiffness matrix Kg(ω-k) in the frequency-wave number domain of the layered ground (Kausel and Rosset 1981).
For each layer of the layered ground the parameters necessary to dynamically characterise the soil behaviour at very small deformations level are the mass density *r*, the shear wave velocity *Vs*, the shear damping ratio *Ds*, the Poisson coefficient *u* and the thickness *h*. The lowest layer is unbounded, that is a semi-infinite half-space. In order to rigorously predict the soil behaviour under dynamic loading, the degradation curve of the shear stiffness *G* and the variation of the shear damping ratio *Ds* as a function of the strain level, as well as of many other soil parameters (overconsolidation ratio, plasticity index, friction angle, void index, effective stress, etc..) should be determined by means of both in situ and laboratory tests. Nevertheless in a simplified analysis a linear equivalent approach can been adopted for soil behaviour, provided that the soil parameters which are used in the analysis correspond to the actual level of deformation, which is experienced by the ground. Actually the region of ground strictly at contact with the track experiences a higher level of deformation with respect to the farest portions of ground, hence soil parameters should vary at different distances from the track. Also at the same location the wave motion and the strain level depend on the train speed *V*. The shear stiffness *G* (or equivalently the shear wave velocity *Vs*) and the shear damping ratio *Ds* to be used in the following charts may be assumed to refer either to the very small strain level or to the linearly equivalent values, which correspond to the actual level of deformation.

2.4. Basic Equations

In the simplified analysis only the vertical displacements and forces have been considered, since rotations and bending moments as well as horizontal displacements and horizontal forces have been ignored.
The vertical equilibrium of forces acting on the track (equation 3) and the ground (equation 4) can be written respectively as:

$$L_t - L_{tg} = K_t \cdot w_t \quad (3) \qquad L_{gt} - L_g = K_g \cdot w_g \quad (4)$$

where Lt are the external loads applied by the train wheels to the track, Ltg=Lgt are the interaction forces at contact nodes between the track and the ground, Lg=0 are the external loads directly applied to the ground, Kt and Kg respectively are the dynamic stiffness matrices previously defined in paragraphs 2.2 and 2.3, w_t and w_g respectively are the relative displacements of the track and the ground.
By summing equations (3) and (4) the vertical equilibrium of forces acting on the whole system (track plus ground) is determined in equation (5). Since the contact between the track and the ground at the interaction nodes is assumed to be preserved in time, the compatibility condition for the displacements can be written as in equation (6).

$$L_t + L_g = \left(K_t \cdot w_t + K_g \cdot w_g\right) \quad (5) \qquad w_t = w_g = w \quad (6)$$

By substitution of equation (6) and considering that no external loads are directly applied to the ground (Lg=0), then equation (5) becomes equation (7):

$$L_t = \left(K_t + K_g\right) \cdot w \quad (7)$$

The wave motion w in equation (8) under the track, at contact with the ground, can be evaluated from equation (7) by knowing the stiffness matrices of the track and the ground and the external loading applied by the travelling train. The corresponding interaction forces at contact nodes in equation (9), transmitted by the track to the ground can be calculated from equations (4) and (8).

$$w = \left(K_t + K_g\right)^{-1} \cdot L_t \quad (8) \qquad L_{gt} = K_g \cdot \left(K_t + K_g\right)^{-1} \cdot L_t \quad (9)$$

3. VALIDATION OF THE MODEL

The method previously presented has been implemented by means of a numerical code Speedy and has been validated by comparing both the vertical displacement and the interaction force under the track (figure 3) which are predicted by Speedy and those which have been measured in Sweden on the West Coast Line during the passage of the high-speed train X2000 (Kaynia et al. 2000, Adolfsson et al. 1999, SGI 1999).

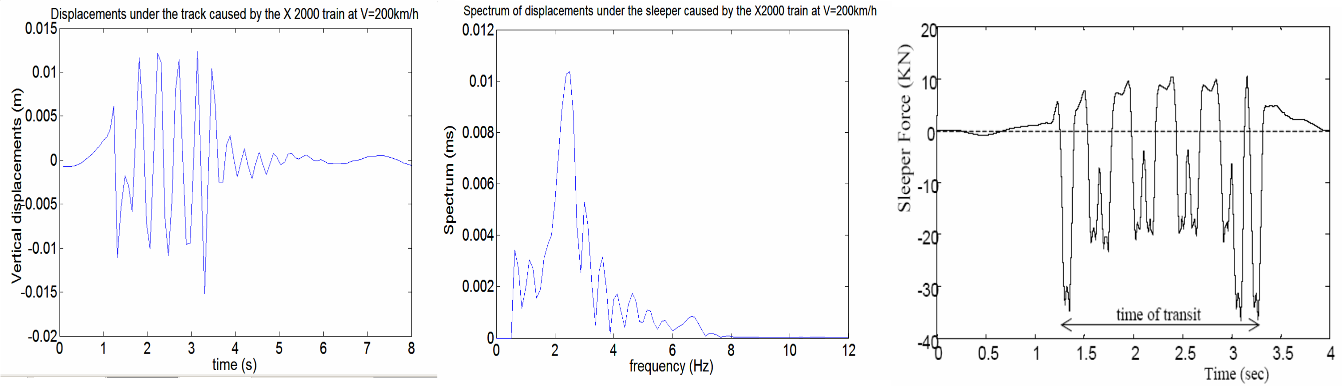

Figure 3. Vertical displacement, spectrum of displacements and interaction force numerically predicted by Speedy under the track during the passage of the high-speed train X2000 at *V*=200 km/h on the West Coast Line in Sweden.

4. PARAMETRIC ANALYSIS

The input parameters of the dynamic SSI among the train, the track and the ground are:

- the position (number, length and spacing of bogies, number, length and spacing of locomotives) and the intensity of the axle loads transmitted by the train to the track through the wheels
- the train constant speed V
- the spacing sd between two consecutive interaction nodes (usually assumed coincident with sleepers spacing)
- the flexural stiffness EI, the linear mass m, the critical hysteretic damping b of the track (rails, sleepers, ballast, base foundation) and the critical frequency w_c at which b is reached

- the mass density *r*, the shear wave velocity *Vs*, the shear damping ratio *Ds*, the Poisson coefficient *u* (or equivalently the compression wave velocity *Vp*) and the thickness h of all the horizontal layers of the ground.

A parametric analysis has been performed in the case of the Italian train ETR 500 Y shown in figure 2. A simplified ground made of one layer over a semi-infinite half-space has been considered. Given the type of train and the characteristics of the track, the key parameters for the whole system response are the shear wave velocity Vs_1 and the thickness h_1 of the superficial layer and the train speed *V*. To these parameters a reasonable range of variation has been assigned (table 1). The train speed varies in the range *V*=(30÷450) km/h. The mechanical and geometrical characteristics of the track system (rails plus sleepers and ballast) are also reported in table 1.

Table 1. Range of variation for the parameters of the layered ground and geometrical and mechanical characteristics of the track.

layer	h (m)	ρ (kg/m³)	Vs (m/s)	Ds (%)	Vp (m/s)	EI (Nm²)	m (kg/m)	sd (m)	ω_c (Hz)	β (%)
superficial	3÷15	1800	50÷500	5.0	100÷1000	$1.25 \cdot 10^7$	610	0.6	0.314	0.1
Half-space	-	2000	1000	3.0	2000					

In the figures 4, 5a, 5b the maximum vertical displacement and the maximum reaction forces, numerically predicted with Speedy under the track during the passage of the train ETR 500 Y, have been plotted as a function of the significant parameters h_1, Vs_1 and *V*. For each analysed combination of the key parameters, together with the maximum displacement also the corresponding frequency f_{max} has been calculated, at which the spectrum of the displacements reaches the absolute peak, i.e. where the main energy of the vibrations is concentrated. The following considerations can be made:

- the stiffer the ground the greater the maximum reaction force under the sleeper, the smaller the maximum displacement and vice versa the softer the ground the lower the reaction force, the higher the displacement
- for thicknesses of the superficial layer of the ground greater than h_1=6 m, no significant variation in the intensity of the displacements and the reaction forces can be observed
- independently from the ground characteristics, several peaks in the system response (both displacements and forces) can be noticed at different train speeds *V*. These peaks suggest the existence of resonance phenomenon, caused by periodicities of the train loads associated with bogies, wheels and sleepers spacings; e.g. the maximum system response at *V*=270 km/h with f_{max}=(20÷25) Hz corresponds to a wavelength $\lambda = V/f_{max}$ =(3.00÷3.75) m, which ranges between bogies and wheels spacings
- for a relatively stiff ground the reaction force under a single sleeper may reach an amplification by a factor of about ϕ_{force}=1.5 times the maximum axle load transferred by an axle to the track; i.e. ϕ_{force}=(260kN/180kN)=1.44; for a relatively soft ground the amplification factor of the maximum static displacement of a beam simply supported by two consecutive sleepers $y_{static}=(F_1 \cdot sd^3)/(48EI)$=0.065 mm may reach values of ϕ_{displ}=(10mm/0.065mm)=154
- vibrations and forces transmitted to the ground are characterised by a main frequency, that is comprised within the range (15÷50) Hz; such vibrations are characterised by wavelengths, which may concern relatively deep layers of ground and may propagate over long distances, due to their moderate material attenuation during propagation (Roma V. 2004)

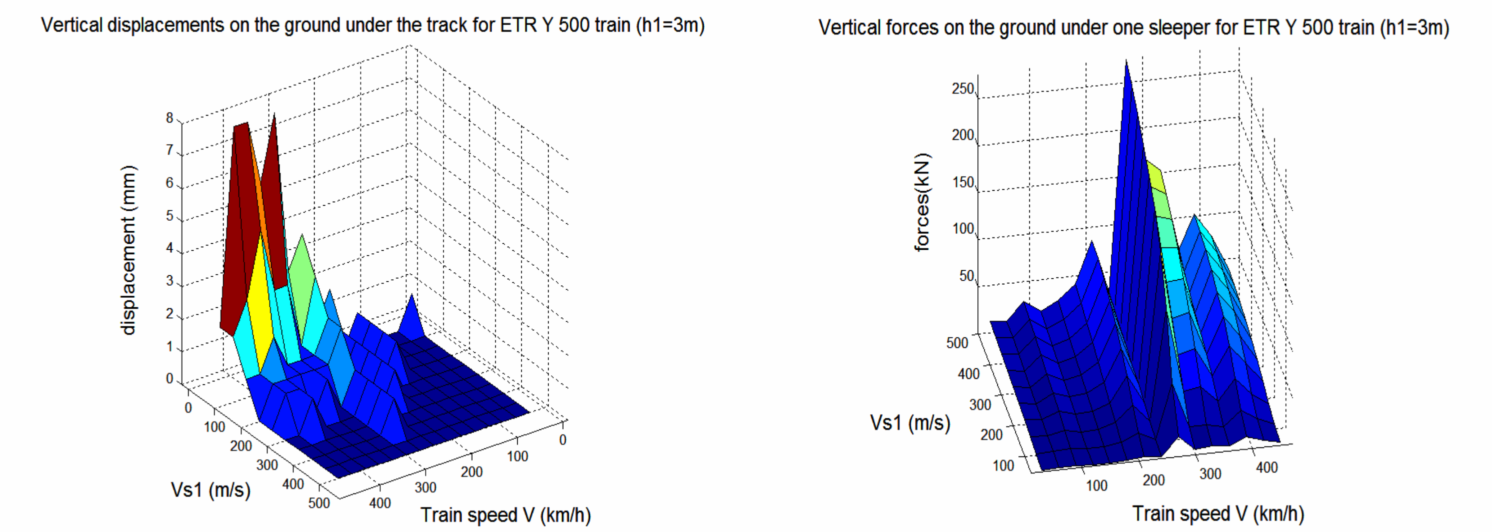

Figure 4. Maximum vertical displacements on the ground surface under the track and maximum reaction forces under one sleeper during the passage of the super-fast train ETR 500 Y for h_1=3m.

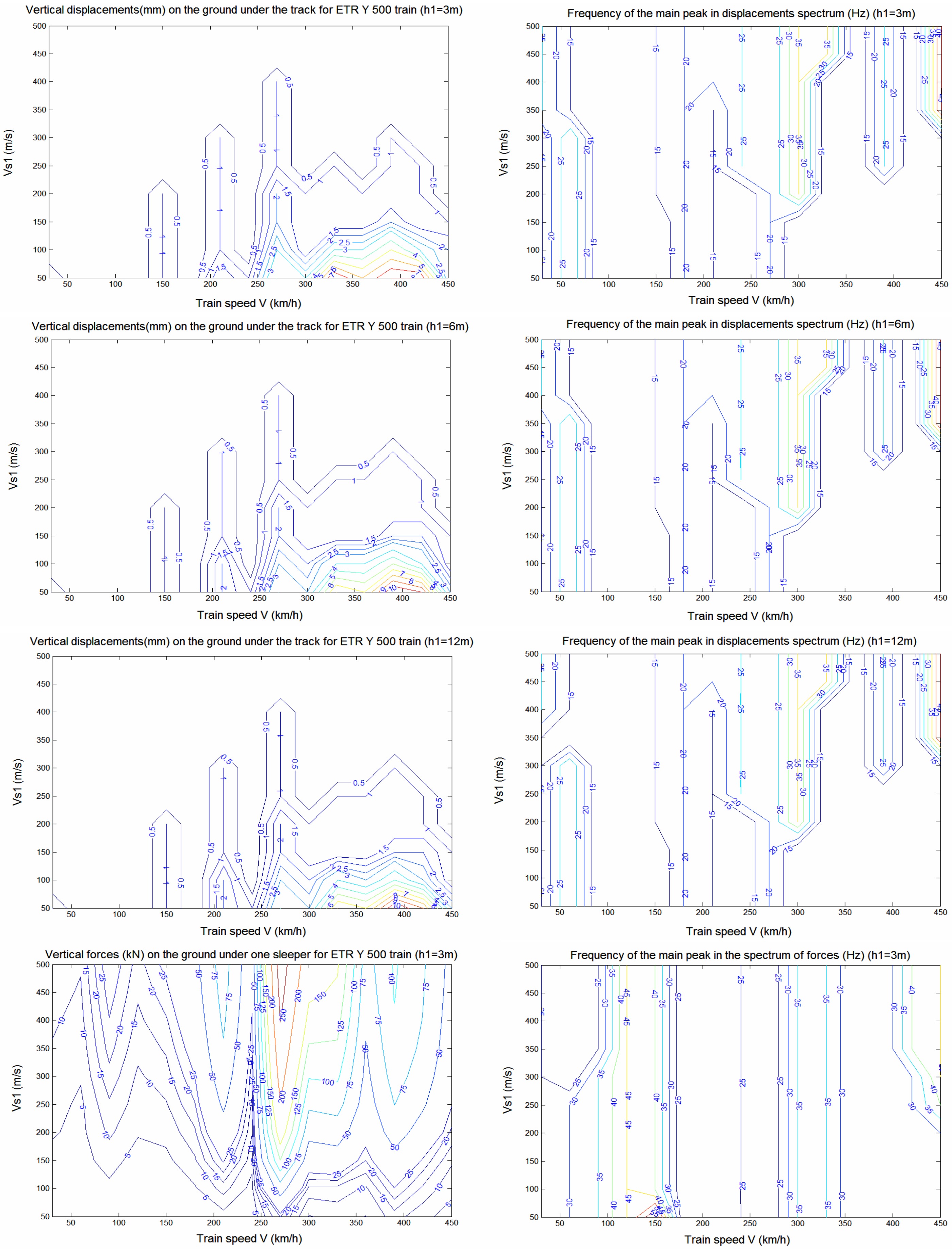

Figure 5a. Maximum vertical displacements on the ground surface under the track and maximum reaction forces under one sleeper during the passage of the train ETR 500 Y for different train speeds *V* and thicknesses *h1* and shear wave velocity *Vs1* of the superficial ground.

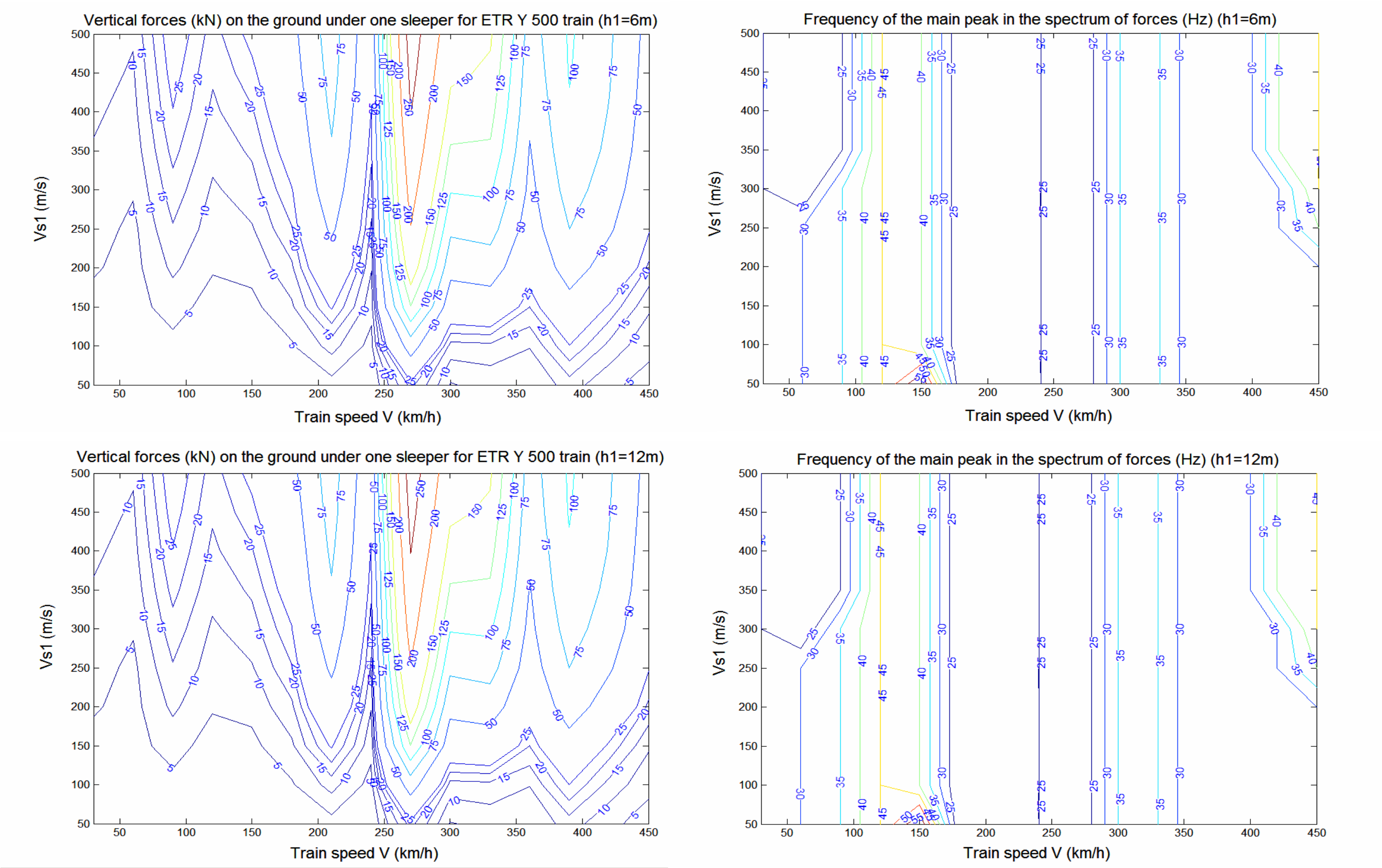

Figure 5b. Maximum reaction forces under one sleeper during the passage of the train ETR 500 Y for different train speeds *V* and thicknesses h_1 and shear wave velocity *Vs1* of the superficial ground.

5. CONCLUSIONS

A code has been implemented for numerically solving the dynamic SSI among the train, the track and the soil, as it is predicted by a theoretical approach. After validation of the results, the method has been used to create a series of graphs, which give the maximum vertical displacement and the maximum vertical forces on the free surface of the ground under the track, for several combinations of the train speed, the shear wave velocity and the thickness of the superficial layer of the ground. The maximum dynamic forces and displacements obtained for the Italian train ETR 500 Y have been normalised with respect to the corresponding static quantities, in order to estimate the amplification factors ϕ_{force} and ϕ_{displ}. With this standpoint the results represent not only an exact solution for the train ETR 500 Y, but also they give a useful preliminary means to be used for design and study of the environmental impact caused by other travelling super-fast trains.

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