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Railway Traffic Vibration Impact Analysis on Surrounding Buildings by FEM—Case Study: TER (Regional Express Train) Dakar—AIBD

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Abstract

The vibrations induced by railway traffic can affect the stability of structures, buildings and buried structures. To evaluate this impact, this study was carried out considering the case of the Regional Express Train which will connect Dakar to Blaise Diagne International Airport. For that, the modeling software Plaxis dynamic [1], able to generate harmonic loads, is used and permitted to have a dynamic analysis and comparison between static and dynamic load for one passage of the train for 2.56 s. In the modeling, two behavior laws were used those of Mohr Coulomb for the layers of soil, embankments and the form layer, and then the linear elastic model for the rest of the elements. The results obtained showed extreme vertical displacements 40.18 mm for the building and when no load is applied on the track, there was 40.24 mm for a static load, and 40.17 mm for a dynamic load. Also, it was observed for the track a displacement of 33.73 mm for a static load and 19.83 mm for a dynamic load. However, further studies are necessary to take into account the permanent deformation after an accurate cycle of train passage in order to better evaluate the railway traffic impact.

Keywords

FEM, Modelling, Impact, Vibrations, Railway, Traffic, Harmonic Loads

1. Introduction

Several authors have worked on the response of structures and soil subjected railway traffic solicitation in particular to consider it as dynamic and cyclic. The most studied models seem to be those using the finite element method as they make it possible to model complex geometries, the modeling of vibratory phenomena in the soil taking into account the problems of reflection on the boundaries of the mesh domain. In order to remedy this, authors have found alternatives either by using the absorbing boundaries or by coupling it to the methods of the border elements [2]. Many technical records have been reported on railway settlement induced by traffic loadings ([3] [4] [5]). Therefore, the railway traffic vibration analysis is very important to predict railway track settlement as well as the settlement of structures around the project. In Senegal, the TER line is divided into a clayey context and a sandy context. The following geological formations were encountered along the project: sands, clays, marl-limestone and embankments. Each of these formations has been the subject of identification tests and mechanical tests *in-situ* and in the laboratory in order to determine the mechanical characteristics [6]. In the study of railway dynamics, the comprehension of the type of loading induced by rail traffic and the way in which it is supported in numerical modeling are very important. However, the "dynamic analysis" module of Plaxis software makes it possible to model the dynamic loads in particular harmonic conditions. This paper aims to present the first simulation results for the involved research. In the first section, a literature review is presented and is necessary to understand all the modeling aspects involved in railway traffic vibrations. In the second part, a simulation with the dynamic module of Plaxis software is presented taking the case of the sandy context and shows the results for one dynamic passage of the train for 2.56 s.

2. Literature Review

2.1. Rail Load Characterization

When a train moves along the track, each of its wheels in contact with the rail interacts with the track. The defects on the wheel and on the rail produce a force of dynamic interaction between the rail and the wheel, of frequency corresponding to the speed of passage over the size of the defect [7]. Railway demands are dynamic and characterized by a large number of cycles, up to a million axles per year for the most frequented LGVs (High Speed Railway Lines) [8]. The track carries a static load due to the self weight applied to the axle and a dynamic overload due to the dynamic interaction between the rail and the vehicle. In interaction with the vehicles, the track supports vertical, transverse and longitudinal overloads (**Figure 1**). The longitudinal forces due mainly to acceleration and braking are small (they may however possibly pose problems on some structures). Vertical and lateral forces are larger and cause different effects [9].

The actions acting on the structures can be classified in deterministic and random solicitations. Deterministic solicitations are periodic (harmonic or anharmonic), impulsive or maintained according to their form of variation over time. As for the case of railway stresses, they are modeled in the form of periodic harmonic solicitations characterized by several loading cycles [10]. A harmonic load is typically that generated by a rotating machine. The solicitation is described by a sinusoidal function (**Figure 2**).

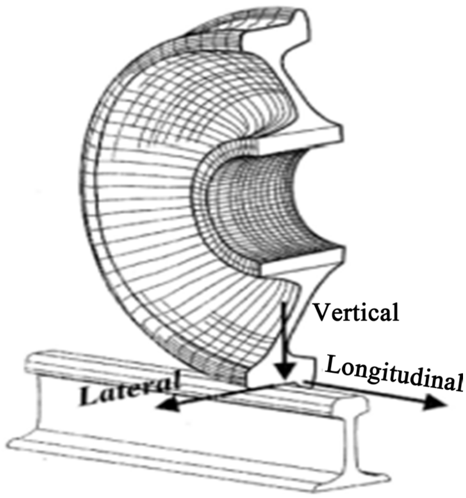

Figure 1. Direction of the forces induced by the wheel-rail interaction [9].

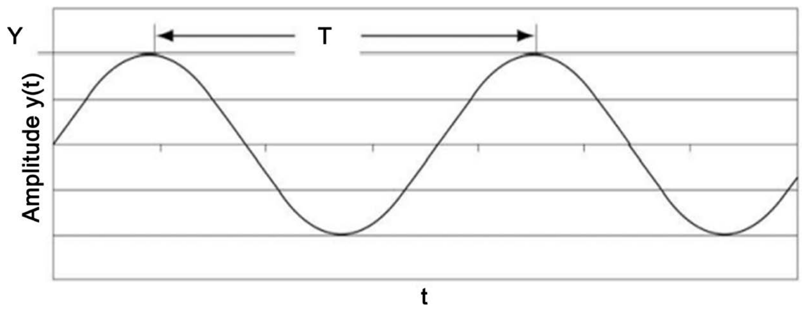

Figure 2. Harmonic loading [10].

$$y(t) = A\sin(\omega_0 t + \theta) \quad (1)$$

$y(t)$: simple harmonic function;

A: represents the amplitude. This is the maximum value of the harmonic function;

t: time variable (s);

θ: phase angle at the origin of the function (rad);

T: period;

ω: pulsation (rad/s).

2.2. Soil Behavior under Dynamic Stress

The empirical laws of two-parameter cyclic behavior traditionally used by the engineer are insufficient to model the dynamic behavior of the soil in large deformations. If one tries to simulate the classical results in the laboratory, the Hardin-Drnevitch hysteretic cyclic law [11], although able to adequately represent the secant modulus of deformation with only two parameters (G_o, α), where G_o is the shear modulus at small deformations and α a non-linear parameter of the model, proves to be inadequate for medium and strong deformations. To overcome this limitation, an empirical law with three parameters (G_o, α, β) is proposed where β is the damping parameter. As in the initial law, the parameter G_0

characterizes the small deformations and the parameter a reports the secant modulus. The additional parameter β makes it possible to correct the Masing's law [12] in order to adapt the theoretical damping coefficients to the experimental results with strong deformations [13]. By way of illustration, we present the experimental form of the stress-strain curve of the soil obtained during cyclic loading (**Figure 3**). Research ([11] [14]) classifies soil behavior into four distinct domains according to the magnitude of strain for any type of cyclic stress:

The field of very small deformations ($\varepsilon < 10^{-5}$);

The field of small deformations ($\varepsilon < 10^{-4}$);

The field of mean deformations ($\varepsilon < 10^{-3}$);

The field of large deformations ($10^{-3} < \varepsilon$).

2.3. Railway Traffic Modeling

In the literature, the structure of vehicles is often modeled by a complex multi-axle system of masses-springs-dampers. The calculation of lane structures can be simplified by considering the vehicle as a load or a group of loads [15]. The charges can be fixed or mobile. The amplitude can be constant or harmonic etc. The simplest models concern for example point or linear loads and make it possible to apprehend and to better understand the physical phenomena involved. Then we define a charge in motion; this load can model a car or a train where one generally considers the fixed reference (O, x_1, x_2, x_3) and the movable reference (P, x, y, z), where P is the point of application of the load and $x = x_1 - ct$, $y = x_2$, $z = x_3$ (**Figure 4**).

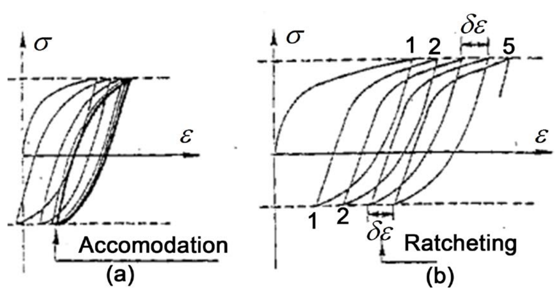

Figure 3. Cyclic stress-strain loading curve [11].

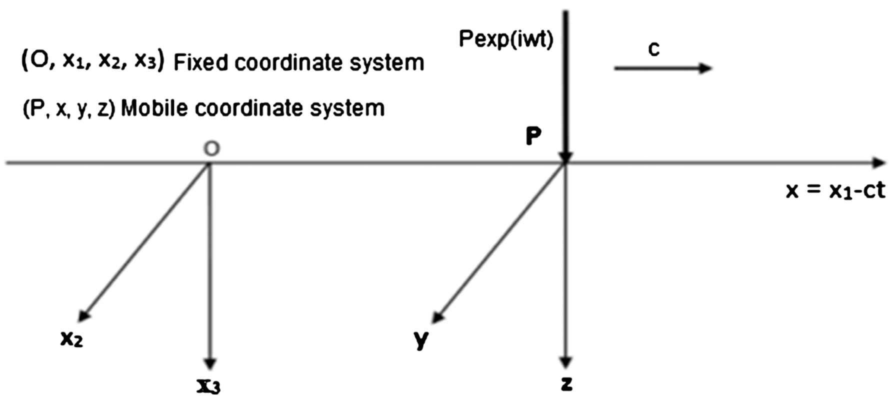

Figure 4. Definition of the axes of the fixed marker and the movable marker [15].

2.4. Modeling of the Railway Structures

Different models for railway structures given by the literature are presented below:

- The rails: The simplest model (and also the most used) is Euler Bernouilli's beam [16]. The Timoshensko hypothesis is also used to take into account more precisely the influence of shear influence [17];
- The soles: They are not always taken into account in the calculations. If they are to be taken into account, they can be considered as a shock absorber [18];
- The sleepers: They are quite rigid compared to the other components. They can be a point mass in a 1D calculation or a rigid body of 3 or 6 depending on the 2D or 3D case. In the 3D case, the sleepers of 2 blocks are linked by a beam which represents the spacers [19].
- Ballast: This is a very difficult point in the modeling of railways because of its discrete properties. For a simpler 1D model, it can be modeled by a continuous system of springs whose mass is uniform [20]. The problems in 2D or in 3D propose models either continuous elastic [21] or not -linear [22] or discrete [23], etc.
- The platform and the ground: The 1D models consider the infrastructure as a system of springs, says the foundation of Winkler. In 2D or 3D calculations, they are often modeled by an infinite multilayer medium. The behavior of the soil can be linear or non-linear depending on the type of materials (Tresca, Coulomb, Drücker etc.) [24] (**Figure 5**).

2.5. Some Numerical Calculations Used for Soils Modeling

In the literature, the most widely used models for soil modeling are: the finite element method (FEM), the boundary element method and the coupling between the two finite element and boundary element methods [25]. The finite element method is very efficient because of its ability to model complex geometries. But this approach is not directly adapted to the study of the propagation of waves in the soil, the propagation of which extends "to the infinite ". Thus, wave reflection at the end of the final domain of computation poses problems when harmonic (steady state) excitation is studied [26]. Authors have sought alternatives to overcome this limitation ([27] [28]) to estimate the nodal efforts to be made on the lateral boundaries to obtain "absorbing boundaries" for the case of planar or axisymmetric geometries to allow the absorption of energy of any type. Other authors have considered coupling the finite element method FEM to that of the boundary elements (BEM) ([25] [29]), or to use only the method of the elements of borders [2] (**Figure 6**).

3. Vibrations Impact Modeling—Case Study: TER Dakar—AIBD

3.1. Presentation of the Input Data

The train has a speed of 160 km/h with a capacity of 500 people/ram. The axle load is 225 kN with a Track spacing of 1.435 m. The sandy context is composed

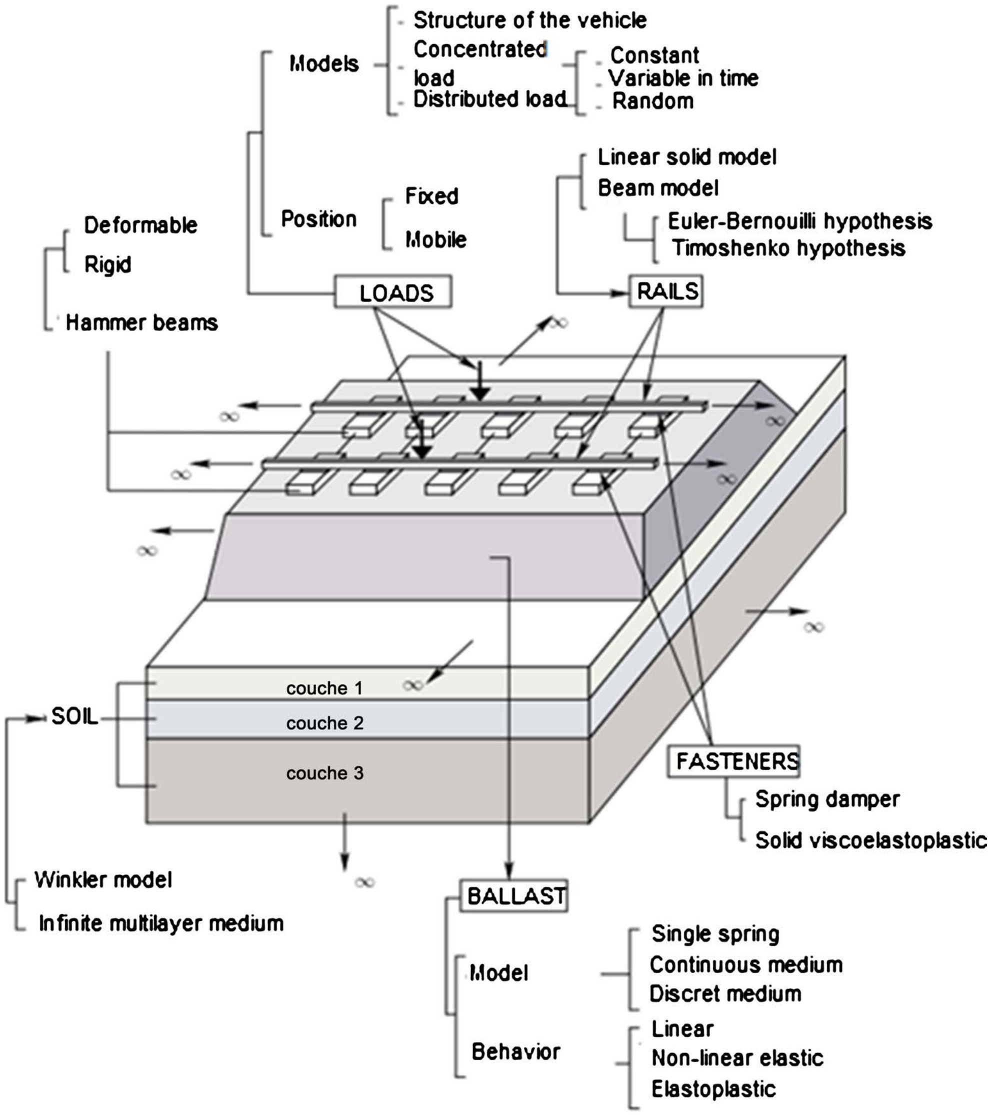

Figure 5. Modeling of railways [24].

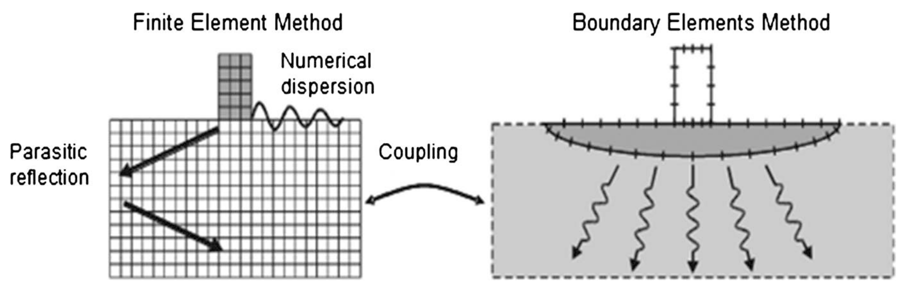

Figure 6. Finite Element Method (Left) and Border Element Method [2].

of 2 major layers: a layer of sand dune of 10 m thick resting on a large layer of silty clay or "Formation de l'hôpital". The materials used for the different layers are composed of: a form layer of gravel lateritic soil, a Basalt layer of 0/31.5 and a Ballast layer of 31.5/50 (where d/D represents the granular class in terms of the lower (d) and upper (D) dimensions of the sieve expressed in millimeters.). **Fig-**

ure 7 presents the geometry of the model. For the soil, the Mohr-Coulomb model is considered. The parameters are given in **Table 1**. The properties of rail beam elements and buildings are given in reference to [30] and [1] (**Table 2**). For the Track, a linear model is considered for all elements. The values of k_x and k_y are given by $k_x = k_y = 1.157 \times 10^{-13}$ m/s for clay and marl a nd $k_x = k_y = 1 \times 10^{-7}$

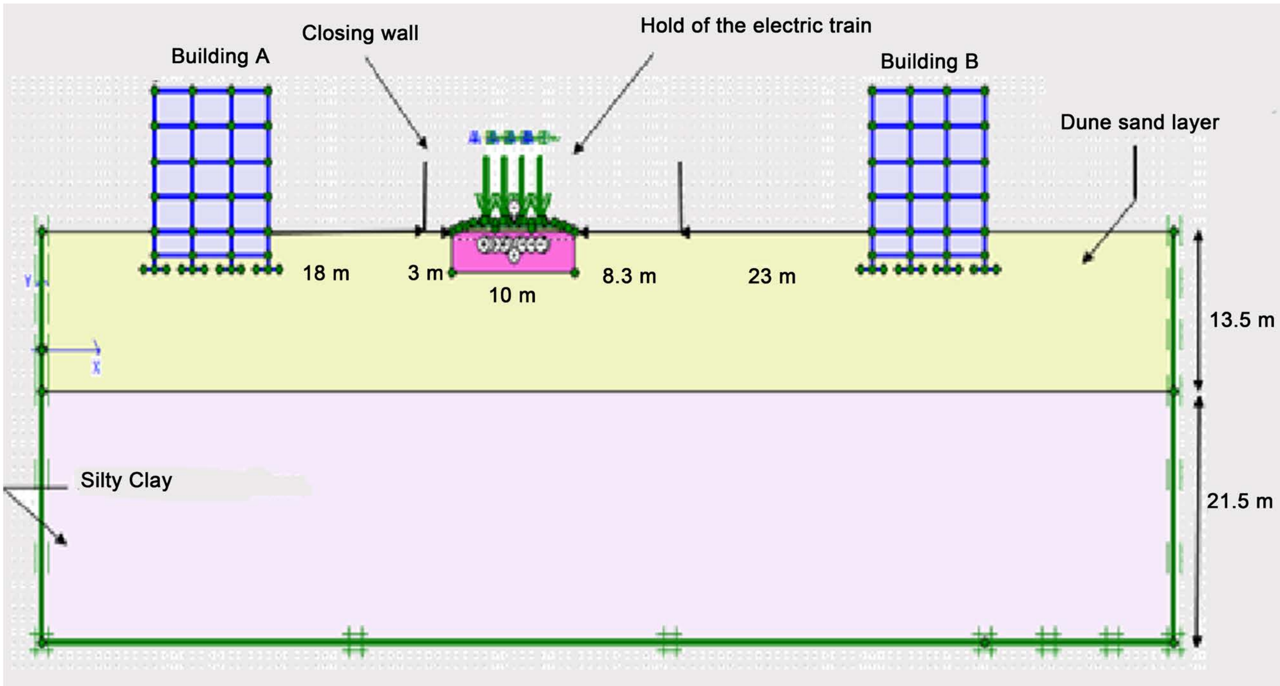

Figure 7. Geometry of the TER model.

Table 1. Materials properties ([6] [30]).

Layer	Behavior Law	Parameters										
		E (kN/m²)	γ_h (kN/m²)	γ_d kN/m²)	c (kPa)	φ (°)	N []	ξ []	α []	B []	K_x m/s	K_y m/s
Ballast	Linear Elastic	2.105	18	17	-	-	0.1	0.01	0.25	0.0003979	10^{-13}	10^{-13}
Under Ballast	Linear Elastic	3.105	25	24	-	-	0.2	0.01	0.25	0.0003979	10^{-9}	10^{-9}
Form layer	Linear Elastic	1.5.105	20	19	1	32	0.2	0.01	0.25	0.0003979	10^{-9}	10^{-9}
Backfill	Mohr-Coulomb	5.104	20	19	1	32	0.3	0.03	0.7539	0.001193	10^{-8}	10^{-8}
Sand dune	Mohr-Coulomb	12000	17.6	15.6	2	32	0.333	0.03	0.754	0.001193	3.9×10^{-6}	3.9×10^{-6}
Silty clay	Mohr-Coulomb	18270	17.8	15.8	8	22	0.3	0.03	0.754	0.001193	10^{-7}	10^{-7}

Table 2. Rails and beam elements properties ([1] [30]).

Structures	Parameters			
	EA (kN/m)	EI (kNm²/m)	W (kN/m/m)	d_{eq} (m)
Rail	1.44×10^6	4930	0.55	0.202
Building	5.106	9000	5	0.147

m/s for silty clay. For the dynamic parameters, the frequency is determined as follows [7]:

$$f = v/L\,; \tag{2}$$

v: speed of the train (km/h),

L: distance between the sleepers (m)

The amplitude is calculated by the Nguyen method [24]:

$$A = P_{stat} + \alpha P_{stat}\,; \tag{3}$$

P_{stat}: static load of the wheel ($P_{stat} = Q/2$ avec Q the axle load)

α: representing coefficient of dynamic forces varying from (0.1 to 0.5)

The simulation was carried out considering 3 loading cases:

Case 1: Case where no load is applied. The movements correspond to a settlement of the building under its own weight;

Case 2: Case of a static load corresponding to a parked train;

Case 3: Case of a dynamic load. For the calculation time, the distance 113.7 m (half the length of the train Thalys) on the speed 160 km/h that gives us a passage time of 2.56 seconds.

3.2. Results and Discussions

The first simulation (Case 1) shows a vertical displacement u_y of 40.15 mm under building B, 40.16 mm under building A and 18 mm under the track (**Figure 8**). This displacement corresponds to a settlement of the building under its own weight.

In the second simulation (Case 2), the value of the displacement is 40.23 mm for building B and 40.24 mm for building A (**Figure 9**). Below the track, a

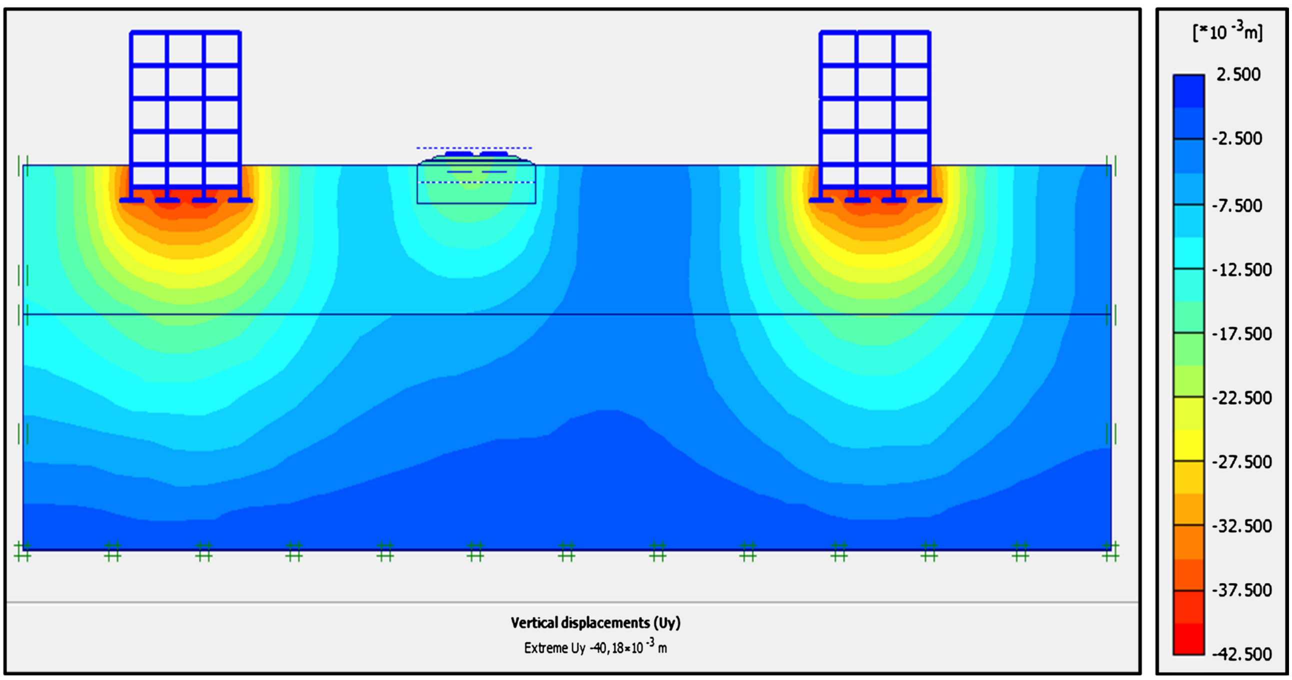

Figure 8. Vertical displacements without applied load.

settlement of 33.73 mm is observed.

In the third simulation (Case 3), a displacement of 40.16 mm is noted for the building B and 40.17 mm for building B_2 (**Figure 10**). Under the track, a settlement of 19.85 mm is observed.

The maximal vertical accelerations give a value of 8.72 m/s^2 (**Figure 11**).

The results showed that depending on the type of loading, the influence is very sensitive at the level of the track. The settlements are more important in the

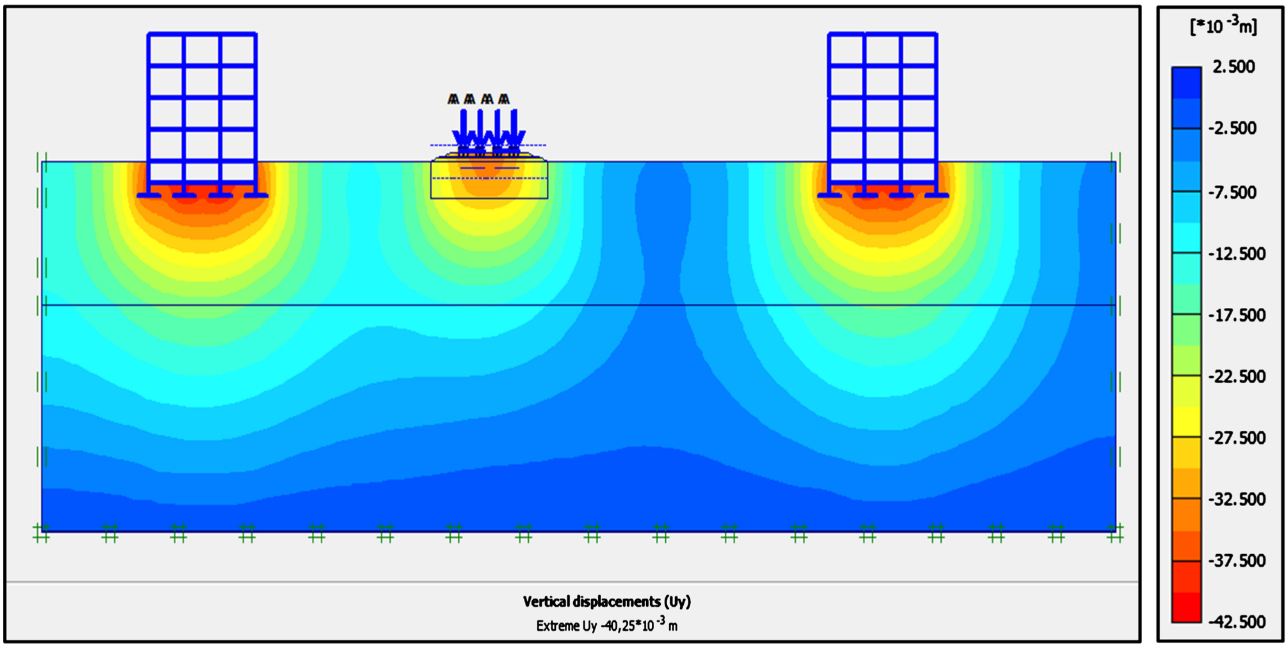

Figure 9. Vertical displacements with static load.

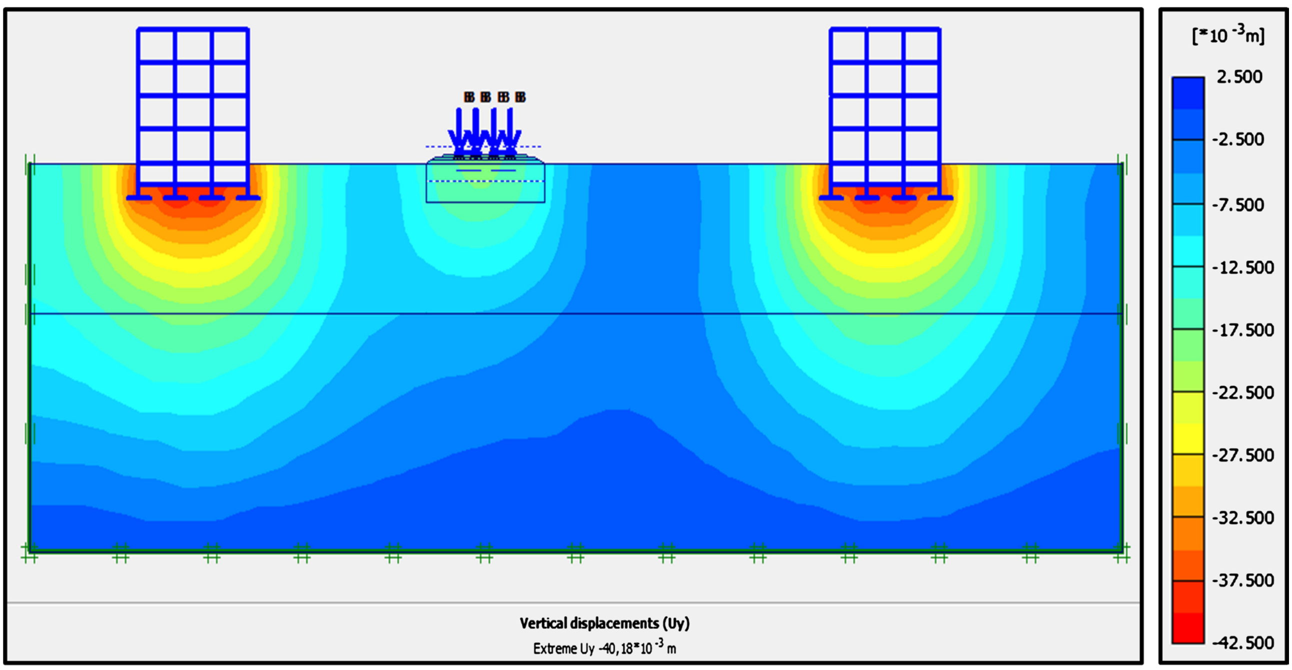

Figure 10. Vertical displacements with dynamic load.

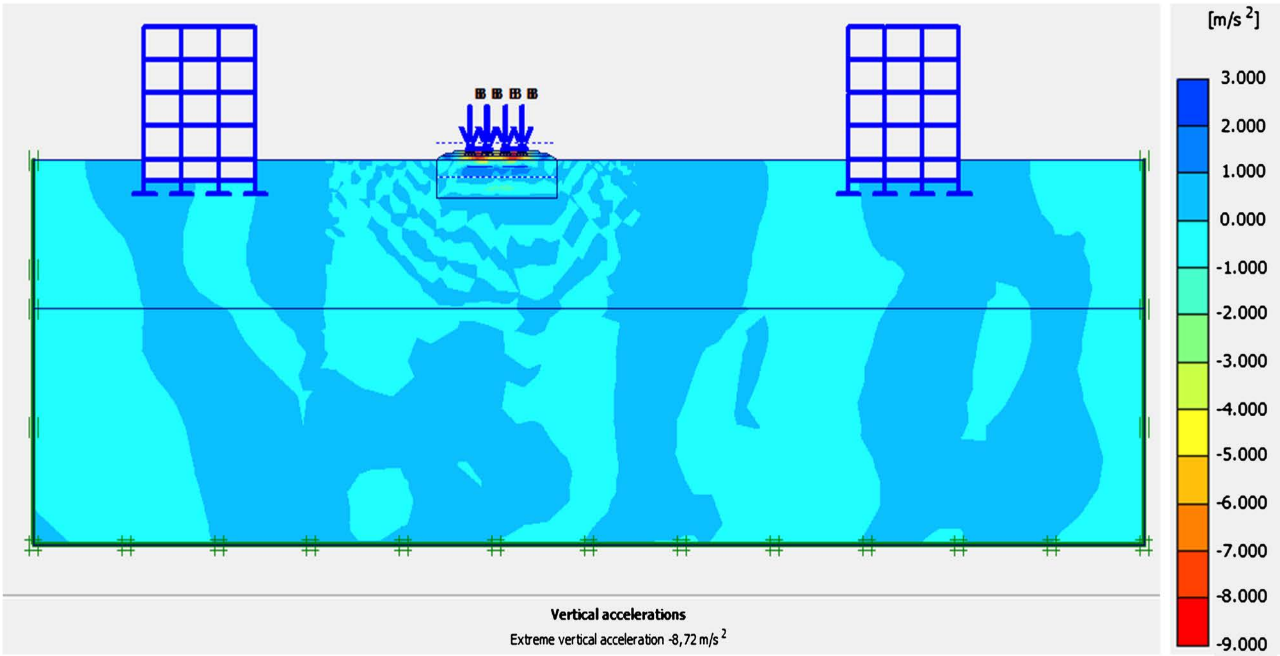

Figure 11. Illustration of vertical accelerations in the model.

Table 3. Summary of the simulations results.

Type of loading	Displacements (m)		
	Track	Building A	Building B
Without load	18×10^{-3}	40.16×10^{-3}	40.15×10^{-3}
Static load	33.73×10^{-3}	40.24×10^{-3}	40.23×10^{-3}
Dynamic load	19.85×10^{-3}	40.17×10^{-3}	40.16×10^{-3}
Impact	-13.88×10^{-3}	-0.07×10^{-3}	-0.07×10^{-3}

track than for the surrounding building. A gap of 13.88 mm is observed between static load and dynamic load for one passage of the train (**Table 3**). The further one gets away from the loading source, the more the influence fades. Buildings A and B are not affected when only one dynamic load is applied.

4. Conclusion

Post-settlement of a railway structure is mainly caused by the self-weight of the embankment and train traffic loadings, and field measurements show that dynamic loading from train traffic has a greater contribution [31]. These first numerical simulations give us a first glimpse of the study of the impact of the railway traffic vibrations. However, they do not allow us to conclude on the effect of the vibration on several cycles of rail loading. Further studies are then necessary to predict the accumulated deformation in railway track and should take into account the repeated triaxial test data. This study must also be validated by the use of experimental methods including instrumentation and *in situ* measurement with geophysical methods, laboratory tests, such as the resonant column which will also allow us to know the impact of vibrations on soil samples.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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