# 761. Study of wave barriers design for the mitigation of railway ground vibrations

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**Abstract.** Nowadays, the consolidation of the rail in highly populated areas has become a reality. Foundations, buildings, high accuracy devices and people are susceptible to suffer from vibrations induced by passing trains. Therefore, models for predicting ground vibrations are required in order to determine new mitigation measures. Rectangular open or in-filled trenches are a suitable solution to be used near constructed railway lines. Their installation is fast, easy and economic since no intrusion in the track is needed. In this work, the influence of the trench design on its effectiveness is analyzed considering a train moving with subsonic speed. A finite element model of the track has been developed and validated with real data registered along the tram network in Alicante (Spain). The analysis is carried out in the time domain considering the quasi-static movement of the vehicles. The results demonstrate that, in ascending order, the most relevant parameters in a trench are its width, depth and in-filled material or trench typology. However, it is also concluded that other conditions such as the stratification of soil are essential in order to determine an optimal design of a wave barrier.

**Keywords:** ground vibration, finite element method, isolation, reflection, wave barrier.

**Nomenclature**

| | |
|---|---|
| $H$ | Trench depth |
| $L_R$ | Rayleigh wavelength |
| $c_{ij}$ | Reflection barrier coefficient |
| $\rho_i$ | Soil density |
| $\mu_i$ | Soil shear wave velocity |
| $\rho_j$ | In-filled material density |
| $\mu_j$ | In-filled material shear wave velocity |
| $\theta_i$ | Incident wave angle |
| $\theta_j$ | Refracted wave angle |
| $\boldsymbol{F}_{\mathbf{ext}}$ | Applied external forces vector |
| $\boldsymbol{F}_{\mathbf{int}}$ | Internal forces vector |
| $\{\boldsymbol{u}\}$ | Nodal displacements |
| $\{\dot{\boldsymbol{u}}\}$ | Nodal velocities |
| $\{\ddot{\boldsymbol{u}}\}$ | Nodal accelerations |
| $[M]$ | Mass matrix |
| $[C]$ | Damping matrix |
| $[K]$ | Stiffness matrix |
| $\{F^a(t)\}$ | Time-dependent vector of applied forces |
| $\alpha$ | Mass-controlling Rayleigh coefficient |
| $\beta$ | Stiffness-controlling Rayleigh coefficient |
| $[\varnothing]$ | Mass normalized eigen vector matrix |
| $[c]$ | Diagonalized damping matrix |

| | |
|---|---|
| $\omega_i$ | Natural system frequency |
| $\xi_i$ | Modal damping ratio |
| $P_{frec}$ | Main frequency spectrum peak |
| $d$ | Distance between consecutive nodes |
| $v$ | Tram velocity |
| $E$ | Young modulus |

## 1. Introduction

In the last decades of scientific railway research, the necessity of establishing a methodology to calculate and control traffic-induced ground vibration has grown up.

On the one hand, the increase in the standard of living in society has prompted the requirement of high quality transportation services. Therefore, a more accurate study of railway internalities and externalities has to be performed.

On the other hand, it is well known that ground vibrations from railways may produce problems in nearby foundations and as a consequence, the stability of buildings and people health can be affected. To prevent these problems, trenches and buried walls, as a type of mitigation measure, may provide an important reduction of vibration amplitude after their location. Although this mitigation measure is still in research process, it is a highly recommended solution because of its characteristics. Firstly, its construction does not present any complexity. And secondly, its onsite installation is very economic because for an existing railway line it is not needed to modify its structure.

In this paper, two main objectives have been achieved. The first goal was to create a model based on the finite element methodology for the prediction of ground vibration propagation. This model has been calibrated and validated with real measurements taken along the tram network of Alicante (Spain). The second effort was to apply this methodology to study the influence of some hypothetical designs of open and in-filled trenches located in the same soil, where the above measurements were taken.

In order to create this model, the most relevant publications on the subject have been reviewed. The first models to predict the ground vibration level produced by the railway appeared during the 70s. In [1] and [2], the dissipation mechanisms of vibrations that have to be taken into account to perform an accurate model were discussed. Some years later, [3] and [4] focused their work on the urban railways. The first one completed an analytical study of the vibrations induced by the metropolitan trains in nearby tunnel structures. Later, [4] presented a methodology to obtain the amplitude of vibration considering all the subsystems which take part in the phenomenon: generation-transmission-reception.

Nowadays, in the study of railway induced-ground vibrations two main tendencies are acknowledged, namely, the analytical and the numerical one. In contrast to the numerical methodology, the analytical one provides a continuous solution in all the domains in which the problem is studied. Some of the analytical researches that may be cited include works such as [5] and [6]. However, these analytical studies have an important limitation since their solution is only possible for simple geometries and idealized conditions. Hence, it is essential to use numerical models in order to predict the ground vibration propagation from railways and to investigate new measures for attenuating the vibration [7]. Therefore, the Finite Element method (FEM) has been the methodology selected in this paper. Several authors have also chosen this method in order to study railway vibrations. [8] studied with the FEM the dynamic response of an embedded rail track demonstrating that vibrations increase with the load speed. In 2009, [9] constructed a two-dimensional FE model to study how the wave-propagation was influenced by buried walls. However, a 2D model cannot take into account the wave propagation, geometrical and material dissipation in the longitudinal direction of the railway. That is why, in this paper, a 3D model has been proposed. In contrast, FEM presents a basic disadvantage for reproducing the wave propagation phenomenon. This method pretends to represent a semi-infinite soil by a finite size model. In consequence, several authors use non-reflecting boundaries in order to prevent this problem [10-13]. However, it ends up being a complicated remedy, which is sometimes applicable only when the layered soil is supported on a rigid bedrock base [14]. In this paper, the radiation condition has been achieved by dimensioning the model so that the biggest required Rayleigh wavelength can be developed in all directions (section 2).

Related to the second scope of the paper, the reduction of the ground vibration amplitude due to the influence of active trenches has been studied. Specifically, the most important parameters on a trench design have been taken into account in the analysis, i.e., width, depth and in-filled material or trench typology.

This kind of vibration dissipation measures have been studied for more than 40 years. Firstly, [15] and [16] carried out some field works. They both reached similar conclusions: the reduction of ground vibration is possible only when the depth of the trench is comparable to the Rayleigh wavelength. Moreover, [16] revealed that a 75% of amplitude reduction is possible when the quotient $H/L_R$ is higher than 0.6 for active isolation and for a homogeneous soil, where $H$ denotes the depth and $L_R$ the Rayleigh wavelength. In addition, later theoretical studies such as [14] and [17] agreed with the idea that the most relevant geometrical parameter on the effectiveness of a trench is its normalized depth. Consequently, it is well known that for a homogeneous soil, the isolation of ground vibration by trenches is effective only for medium and high frequency vibrations, so it can be thought that for a homogeneous soil and low wavelengths, trenches could not be very effective**.** However, from that, several authors such as [14], [16] and [18] suggest that it would be necessary to study the influence of barriers in a layered ground since it is expected to find a greater effect than in a homogenous soil. The soil in the study site of this paper is a layered one. In section 4, the interaction among this fact and the depth of the trench is analyzed. Moreover, there is not a great agreement by the main works on the influence of the trench width. Some authors such as [11] and [19] found this parameter to be significant on the trench effectiveness while [12], [16] and [20] reached the opposite conclusion. In order to come to a clear idea, the trench width is also studied in this paper.

Related to the in-filled trench material, the mitigation phenomenon is produced by the impedance discontinuity in the propagation medium since arriving waves are refracted and reflected. In accordance with [21], the reflection coefficient $c_{ij}$ for a determined in-filled trench is defined as follows:

$$c_{ij} = \frac{2\rho_i\mu_i\cos\theta_i}{\rho_i\mu_i\cos\theta_i + \rho_j\mu_j\cos\theta_j} \quad (1)$$

where $\rho_i$ and $\mu_j$ are, respectively, the density and the velocity of the elastic shear waves for the soil and $\rho_j$ and $\mu_j$ are the same parameters for the in-filled trench material. In addition, $\theta_i$ and $\theta_j$ are, respectively, the incident and refracted wave angle. From that, the denser and the stiffer the in-filled material is, the bigger reflection coefficient the trench will have, obtaining a better effective isolation. All this is related to the reflection mechanism, but theoretically, the absorption mechanism could also make the amplitude of vibration reduce in soil after the trench. In section 4, the influence of the in-filled material density and stiffness over trench effectiveness will be analyzed by proposing concrete and polyurethane as in-filled materials. However, in spite of everything, it is well known that, ideally, an open trench will always be better than an in-filled trench since no waves are transmitted at a solid to void interface. This fact has also been studied in the next analysis as two open trench typologies have been proposed: an open trench and a sheet piling trench.

## 2. Development of the 3D FE model

In this section, a description of the methodology followed in the development of the FE model is presented.

As it will be seen below, a three-dimensional finite element method has been used for the study of the induced-train ground vibration waves in the time domain. The geometry and material characteristics of the track and soil elements have been taken from a specific point of the tram network of Alicante where the real data were measured. Consequently, the analysis of barriers presented in section 4 will be applicable in the future.

With this methodology, both quasi-static and dynamic mechanisms of train vibration generation can be implemented. However, when creating the model no dynamic components have been taken into account until the calibration and validation process.

### 2.1 Rayleigh damping theory

For the FEM analysis, the software ANSYS LAUNCHER has been used. In order to resolve the numerical dynamic problem, a global mass matrix $[M]$, damping matrix $[C]$ and stiffness matrix $[K]$ are generated. Then, the equilibrium is proposed by equation (2):

$$\boldsymbol{F}_{\mathbf{ext}} = \boldsymbol{F}_{\mathbf{int}} \tag{2}$$

where $\boldsymbol{F}_{\mathbf{ext}}$ and $\boldsymbol{F}_{\mathbf{int}}$ are, respectively, the applied forces and the internal forces vector. Therefore, based on the values of the state fields (displacements $u$, velocities $\dot{u}$, and accelerations $\ddot{u}$), internal forces are calculated resolving numerically the equation of motion (3):

$$[M]\{\ddot{\boldsymbol{u}}\} + [C]\{\dot{\boldsymbol{u}}\} + [K]\{\boldsymbol{u}\} = \{\boldsymbol{F}^{\boldsymbol{a}}(\boldsymbol{t})\} \tag{3}$$

being $\{\boldsymbol{F}^{a}(\boldsymbol{t})\}$ the external applied forces vector which is time-dependent.

Although the generation of mass and stiffness matrices is performed directly from the system properties, Rayleigh damping theory is considered so as to generate the damping matrix. According to this theory, $[C]$ can be denoted by (4):

$$[C] = \alpha[M] + \beta[K] \tag{4}$$

in which $\alpha$ and $\beta$ are the so-called Rayleigh coefficients which are required for the dynamic analysis and have a global influence in the phenomenon.

By orthogonal transformation, equation (4) is modified as (5):

$$[\emptyset]^T[C][\emptyset] = \alpha[\emptyset]^T[M][\emptyset] + \beta[\emptyset]^T[K][\emptyset] = [c] = \begin{bmatrix} \alpha + \beta\omega_1^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \alpha + \beta\omega_{\mathrm{n}}^2 \end{bmatrix} \tag{5}$$

being $[\emptyset]$ the normalized eigenvector mass matrix of the system, $[c]$ is the diagonalized damping matrix and $\omega_i$ is the i-natural modal frequency of the system.

From analogy to single-degree-of-freedom systems, it is known that:

$$c_i = 2\xi_i\omega_i \tag{6}$$

where $\xi_i$ is the modal damping ratio. Then, matching (5) and (6), equation (7) is obtained:

$$2\xi_i\omega_i = \alpha + \beta\omega_i^2 \tag{7}$$

and this reduces to (8):

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \tag{8}$$

A hypothetical plot of equation (8), considering typical values of $\alpha$ and $\beta$ coefficients is shown in figure 1.

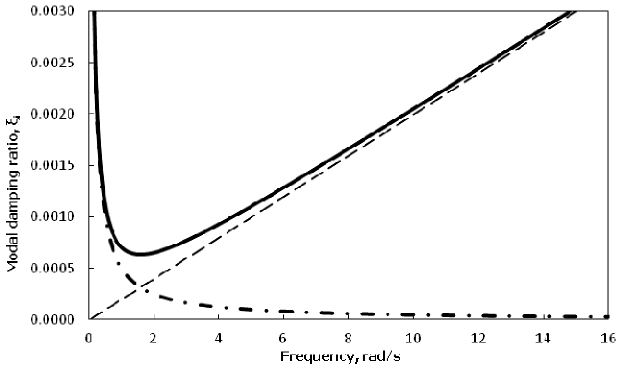


**Fig. 1.** Graphical representation of expression (8):
———, $\xi_i$; ▬ ▪ ▬ ▪, mass component ($\frac{\alpha}{2\omega_i}$); ▬ ▬ ▬, stiffness component ($\frac{\beta\omega_i}{2}$)

As can be seen, the modal damping ratio is non-linear frequency-dependent. Moreover, both mass and stiffness components have been plotted. In this way, it can be observed that the mass component, dominated by coefficient $\alpha$, is only notable for a frequency range from 0 to 6 rad/sec. In contrast, the stiffness component, dominated by coefficient $\beta$, is always notable and proportional to the natural frequency of the system. In a large number of civil problems, the natural frequency values of a system are located in the linear tract of the expression because of the large structural stiffness, see equation (8). Therefore, in these cases it can be assumed that the mass component is not influential in the phenomenon and expression (8) can be written as (9):

$$\xi_i = \frac{\beta\omega_i}{2} \tag{9}$$

Clearing the $\beta$ coefficient from (9), it can be obtained by equation (10):

$$\beta = \frac{2\xi_i}{\omega_i} \tag{10}$$

As an exception, it can be considered the case of a system where a harmonic force or a set of harmonic forces are applied. For the determination of damping Rayleigh properties, $\omega_i$ is to be supposed as the most dominant harmonic force frequency since the system is going to vibrate in accordance with this time-dependent action.

## 2.2 Modeling the railway cross section

Regarding the railway structure modeling, a simplified reproduction of the elements has been determined. Considered actions are vertical, i.e. train weight and hypothetical induced dynamic actions from wheel and rail defects. Consequently, mechanical properties and geometry are modified so that inertia and vertical rigidity are equal to the real ones. A cross section of the studied track is shown in figure 2.

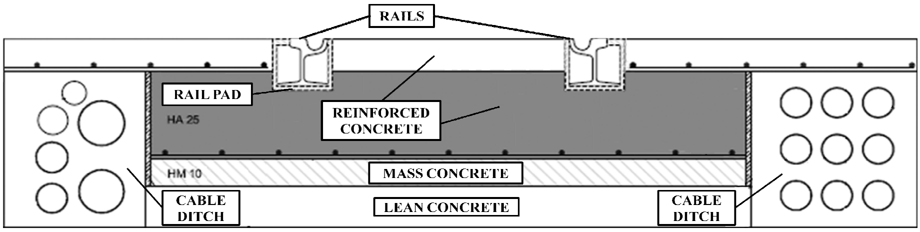


**Fig. 2.** Cross section of the railway provided by GTP (Management Entity of Transport Network and Ports of the Generalitat)

As can be observed, the studied structure is a slab track with embedded Phoenix rails and three different concrete layers, i.e. reinforced, mass and lean ones. Rails have been modeled as a rectangle which has the same width as the real foot rail but different height so that the horizontal axle inertia is the same as the real one. Rail pad thickness has been increased since its actual dimension is too small compared to the other elements. In consequence, Young's modulus has been modified so that the element has the same vertical rigidity as in reality. The same geometry as shown in figure 2 has been modeled for the concrete elements. From geotechnical tests it is known that the soil is formed by a 2 meters thick sand layer supported on a calcarenite bedrock base. However, the sand elastic parameters are still unknown. Material characteristics are summarized in Table 1.

**Table 1.** Material properties

| Material | E (Pa) | $\nu$ | $\rho$ (kg/m$^3$) |
|---|---|---|---|
| Rail | 2.1e11 | 0.30 | 7830 |
| Rail pad | 2.67e7 | 0.48 | 900 |
| Reinforced concrete | 2.72e10 | 0.25 | 2400 |
| Mass concrete | 2.25e10 | 0.20 | 2300 |
| Lean concrete | 2.25e10 | 0.20 | 2300 |
| Cable ditch | 1.13e10 | 0.20 | 2300 |
| Sand | unknown | unknown | unknown |
| Calcarenite | 4.6e9 | 0.26 | 1830 |

## 2.3 Defining the entire FE model

In order to perform a thorough analysis, wave propagation criterion has to be respected. Hence, no artificial boundaries have to interfere on the vibration transmission by creating wrong reflecting and refracting effects. It has been decided to study a frequency range from 2 to 50 Hz, which includes large part of the frequency interval relevant to the whole body perception. Since ground surface vibration is studied, Rayleigh waves are to be considered in the assumptions. Consequently, for calculating the transversal and longitudinal dimension of the model, the largest Rayleigh wavelength at the lower considered frequency has to fit on the model in all directions. Considering the elastic vibration theory, this wavelength corresponds to approximately 50 m. Similarly, the length of the elements is determined so that 6 nodes are present per wavelength of the Rayleigh waves at the higher frequency [22]. In this way, the length of elements is up to 0.5 m.

The vehicle self-weight is applied to the rail as a punctual force. However, the force magnitude has been modified depending on its position since the vertical rigidity of the modeled track is lower near the frontiers. Consequently, track deflections under a unitary force have been analyzed as can be seen in figure 3. In this way, the train weight has been pondered so that the vertical deflection keeps constant along the full movement.

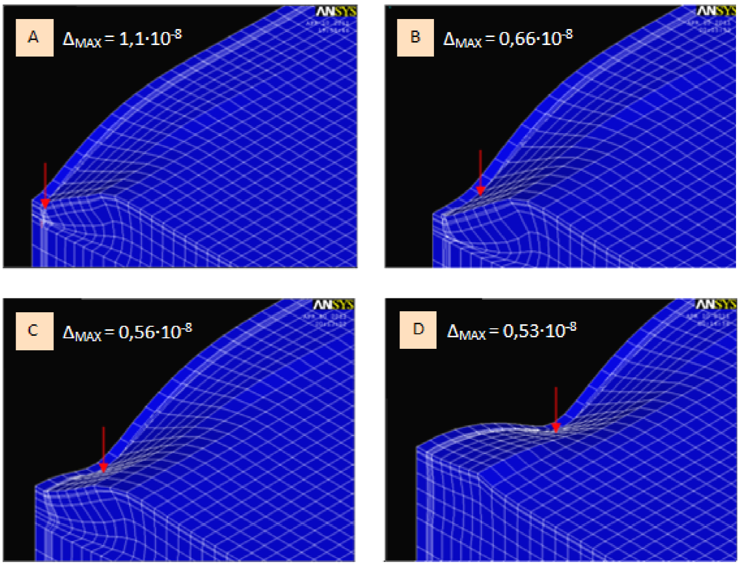


**Fig. 3.** Study of vertical track displacements under a unitary force

Surface soil accelerations are obtained in a track transversal line located in the half of the model, i.e. as far as possible of the beginning and ending model boundaries, see figure 4.

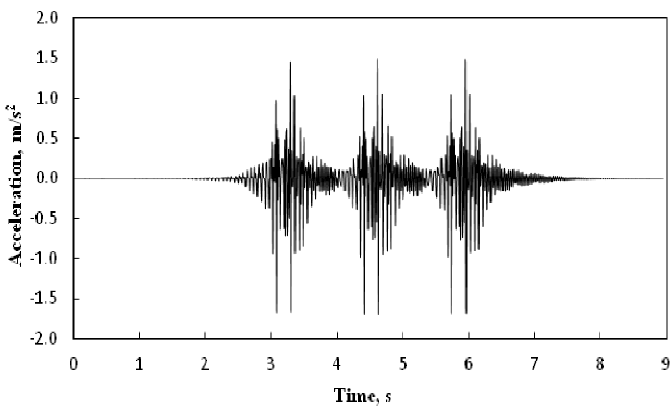


**Fig. 4.** Rail vertical acceleration

Attending to figure 4, the three different vehicle bogies can be distinguished as three maximum accelerations are registered. In addition, three principal peaks in acceleration spectrums have been recognized: bogies and wheels quasi-static frequencies, which are not too dominant, and the main frequency spectrum peak, i.e. $P_{frec}$ = 16.67 Hz, which is induced by discretized progress of the load since the distance between nodes is $d$ = 0.5 m and the considered train velocity is $v$ = 30 km/h:

$$P_{\text{frec}} = \frac{v}{d} = \frac{30/3.6}{0.5} = 16.67\ \text{Hz} \tag{11}$$

To conclude the modeling, different comparisons between initial and simplified model results have been performed and the half part of the structure has been removed since it does not involve any modification on results. This fact has provided a relevant structure simplification since the mesh has become much more economic in terms of computational time.

### 2.4 Sensitivity analysis

It is necessary to establish which parameters that take part in the process are influential in the results and which of them are not. This analysis provides help when carrying out future settings and results comparisons with collected real data, i.e. calibration and validation processes. However, there are some known parameters whose sensitivity analysis would not make sense since their magnitude is already established. Unknown parameters are the global $\beta$ Rayleigh coefficient and the elastic sand properties.

In figure 5, the influence of Young's modulus on accelerations results for a point located 1.20 m far from the rail is indicated. As can be observed, this parameter is quite influential since vibration amplitude decreases for higher values of it. Regarding the $\beta$ Rayleigh coefficient, its effect on the dynamic response is provided in figure 6. It is determined that the higher the $\beta$ coefficient is, the more attenuated the soil response is since the acceleration amplitude and the time-response after peak are lower. This fact can be explained from equations (9) and (10) as the modal damping ratio is proportional to the $\beta$ Rayleigh coefficient. Moreover, in order to propose some appropriate values of coefficient $\beta$ for the sensitivity analysis, equation (10) has been used. Other sand elastic parameters such as the Poisson's ratio and density have been found not to be so much influential on the results.

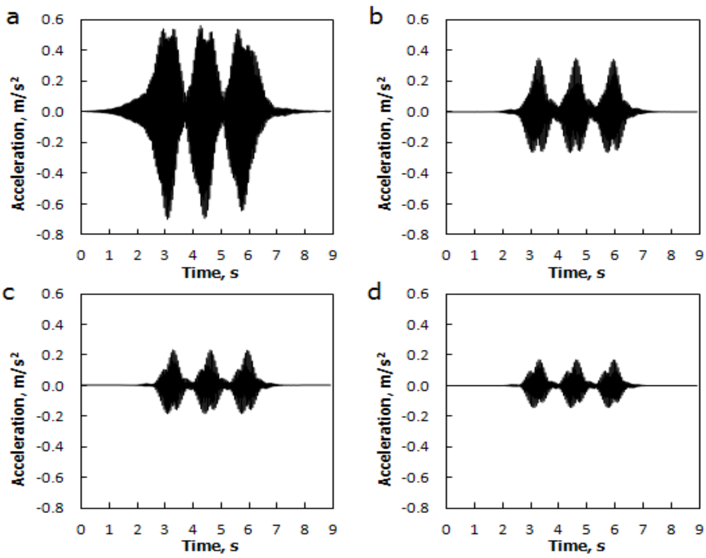


**Fig. 5.** Acceleration response in a point located at 1.20 m distance from the rail for different sand Young's modulus values ($E$): a) $E_1 = 1.7\cdot10^7$ Pa; b) $E_2 = 7\cdot10^7$ Pa; c) $E_3 = 12.3\cdot10^7$ Pa; d) $E_4 = 17.5\cdot10^7$ Pa

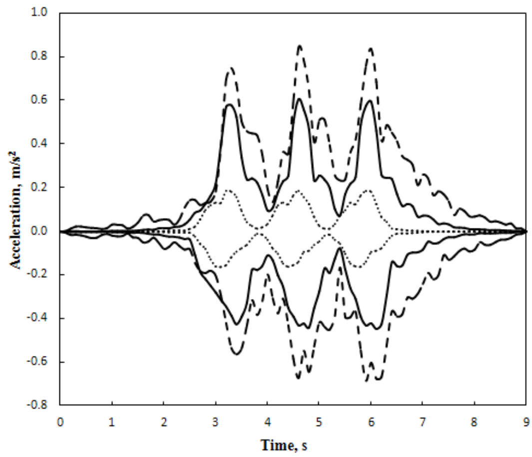


**Fig. 6.** Schematic acceleration response in a point located 1,20 m from the rail for different $\beta$ Rayleigh coefficient: ▬ ▬ ▬, $\beta_1 = 0.0001$; ▬▬▬▬, $\beta_3 = 0.001$; ········, $\beta_4 = 0.01$

Thus, the only two parameters which have been chosen to take part in the calibration and validation processes are the Young's Modulus and the $\beta$ Rayleigh coefficient.

## 3. Calibration and validation

Once the model has been developed, it has been calibrated and validated from the measurements registered on Line 4 of the Alicante tram network. The measurements were taken when the vehicle passed by using some FiberSensingTM tri-axial accelerometers. The data was recorded in two points located 0.3 and 1.20 m far from the rail and only data gathered from trains which speed was approximately 30 km/h have been considered. Hence, the effect of velocity has not taken part in the analysis. The average of all registered accelerations has been obtained and used for performing the comparison since the variability of results has been checked to be acceptable.

As deduced in section 2, the only two parameters considered in the calibration and validation process are those which are influential in results and yet unknown. The rest of the parameters have been provided by GTP or obtained from simple calculus. Both unknown parameters have been calibrated by comparing the model results with data gathered 0.3 m from the rail. The dynamic component has been taken into account by increasing model accelerations in a 33% [23] as, since this point, only quasi-static generation mechanism had been considered.

The calibration process has been rigorously performed by comparing the following criteria between the real data and model results:

- Value of the maximum and minimum acceleration peaks.
- Time the signal takes to grow to the first peak.
- Attenuation time from the last peak.

After that, it has been achieved to validate the model with the suitable chosen parameters by making another comparison. It has been checked that model results accurately fit with the real data collected 1.20 m from the rail. The resulting parameters from the calibration process are listed in Table 2.

**Table 2.** Resulting parameter values from calibration process

| Parameter | Calibrated value |
|---|---|
| $\beta$ Rayleigh coefficient | 0.001 |
| Sand Young modulus | 70 MPa |

The validation process allows the model to study the effectiveness of barriers on wave transmission isolation for the analyzed soil.

## 4. Study of barriers influence in wave soil propagation

In the present analysis, the main influential parameters in a wave barrier design are studied. According to the reviewed literature, it is well known that factors such as the trench geometry, i.e. depth and width and the in-filled material may have a pronounced effect on the trench effectiveness. However, this effect has not been entirely established for a layered soil yet, but it is thought that trench effectiveness may be modified. As has been seen, the analyzed railway track is over a stratified soil so the layering effect has been analyzed. The characteristics of the soil materials are shown in Table 3.

**Table 3.** Soil material mechanical characteristics

| | **Material** | **Thickness (m)** | **E (MPa)** | $\nu$ | **ρ (kg/m³)** |
|---|---|---|---|---|---|
| Upper layer | Sand | 2 | 70 | 0.3 | 1800 |
| Substratum | Calcarenite | indefinite | 4600 | 0.26 | 1830 |

A quasi-static load is applied along the rail at a constant velocity of 30 km/h. The acceleration amplitude after different proposed active trenches is computed. Thus, the influence of trenches characteristics is studied.

### 4.1 Influence of trench width

According to [24], the isolation improvement of a wave barrier is only appreciable for a width below a quarter of the Rayleigh wavelength. In this model, the main propagation frequency is 16.67 Hz and the Rayleigh wave velocity for the upper layer is about 106 m/s. From that, a quarter of the main wavelength is up to 1.6 m, which is not a reasonable dimension for a trench. Hence, widths below this value are studied.

For the present analysis, the effectiveness of three open trenches has been compared. The following widths for each one of them have been considered: 0.45 m, 0.6 m and 0.75 m which are common backhoe bucket sizes and sensible dimensions to be used in urban areas. The trenches depth has always been kept constant and equal to 1.5 m so the calcarenite substratum has not been penetrated. Figure 7 shows the vertical acceleration response in a node located 1.3 m from the trench for each considered width.

Since the main wavelength in the model is lower than the quarter Rayleigh wavelength, the vibration isolation after the open trench grows as the width is larger, which agrees with [24]. However, this dynamic reduction is not so relevant considering that the vibration amplitude for each studied solution has the same order of magnitude. From that, it can be concluded that the slight alteration produced by the increase of the studied parameter cannot justify the choice of the barrier width in the design process. There are some more important design criteria such as the availability of urban space or the construction budget.

### 4.2 Influence of trench depth and typology in a layered soil

The previous analysis suggests that a practical solution should be chosen in order to establish the trench width as no dynamic criteria is to be considered. Hence, in this section, a width of 0.45 m is selected for the study. The following trench depths and typologies are considered:

- 1 m depth, which is the shorter trench studied.
- 1.5 m depth, which base is at distance of 0.5 m from the calcarenite layer surface.
- 2 m depth, which base is in contact with the calcarenite layer surface.

- 2.5 m depth, which penetrates the calcarenite layer 0.5 m.
- In-filled concrete barrier, see Table 4.
- In-filled polyurethane barrier, which is a relatively soft material, see Table 4.
- Open trench.
- Sheet piling trench.

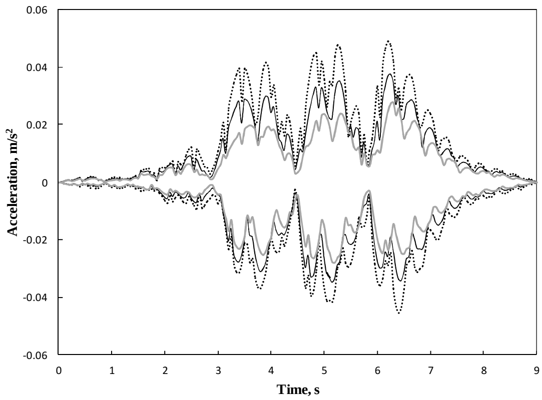


**Fig. 7.** Schematic acceleration response in a node located 1.3 m far from the trench: ········, 0.45 m width; ▬▬▬, 0.6 m width; ▬▬▬, 0.75 m width

**Table 4.** In-filled material characteristics and in-filled trenches reflection coefficient

| | E (MPa) | $\nu$ | $\rho$ (kg/m$^3$) | $c_{ij}$ |
|---|---|---|---|---|
| Concrete | 30000 | 0.25 | 2400 | 0.08 |
| Polyurethane | 20 | 0.45 | 500 | 1.58 |

The influence of depth in the isolation vibration is computed in terms of acceleration registered in the soil after the trench. This analysis is firstly performed for each trench typology separately. The results are provided in figures 8, 9, 10 and 11.

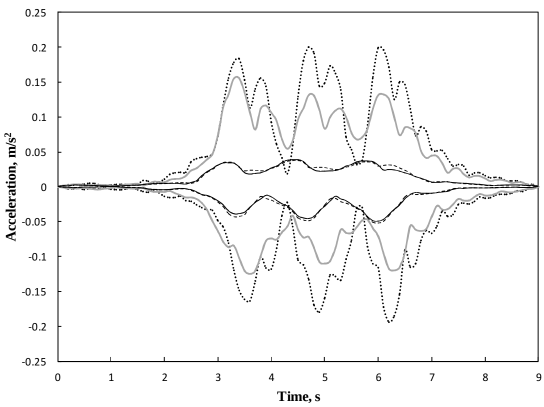


**Fig. 8.** Schematic acceleration response in a node located at 2 m from an in-filled concrete trench: ········, 0.5 m deep; ▬▬▬, 1 m deep; ▬ ▬ ▬, 1.5 m deep; ▬▬▬, 2 m deep

Generally, with the exception of the polyurethane trench, it can be said that an increase of the trench depth induces better vibration isolation only for depths within the sand layer thickness. As can be observed, both depths 1.5 m and 2 m produce the same effect. So, according to this


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model, a penetration in the bedrock base is not necessary since no remarkable improvements have been registered and in general, the optimum depth will be considered the sand layer thickness. In contrast, according to figure 11, the maximum vibration reduction for a sheet piling trench is given by the 1.5 m depth trench so this would make possible to save 0.5 meters of sand excavation.

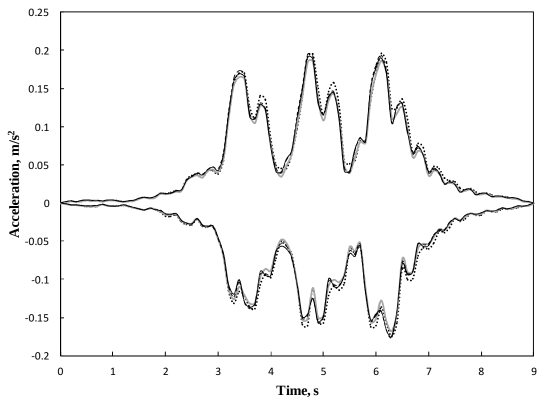


**Fig. 9.** Schematic acceleration response in a node located at 2 m from an in-filled polyurethane trench: ........, 0.5 m deep; ——, 1 m deep; — — —, 1.5 m deep; ——, 2 m deep

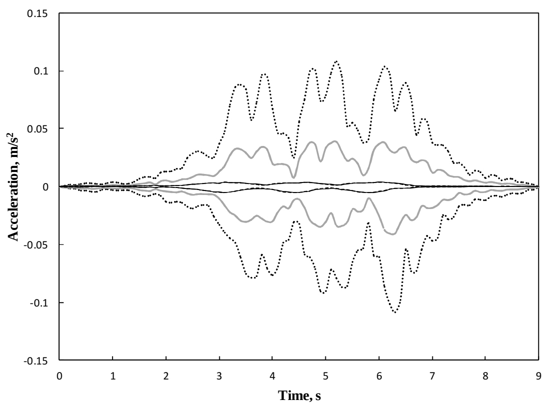


**Fig. 10.** Schematic acceleration response in a node located at 2 m from an open trench: ........, 0.5 m deep; ——, 1 m deep; — — —, 1.5 m deep; ——, 2 m deep

At the same time, however, for the in-filled polyurethane trench, no improvements have been found with depth increment.

To sum up, it has been established that, mainly, the whole vibration energy is propagated by the softer substratum when the soil is stratified. This fact provides a huge advantage for trenches since it is not necessary to reach big depths to achieve a notable vibration reduction level. In addition, it has been revealed that the depth is not highly influential for in-filled trenches, which material has a big reflection coefficient, i.e. polyurethane.

The above results provide a clear idea about the influence of depth in the trench effectiveness. However, in figure 12 the difference between the four considered trench typologies is compared. The maximum acceleration peak for the time acceleration response of a node located at 2 m from the trench is represented.

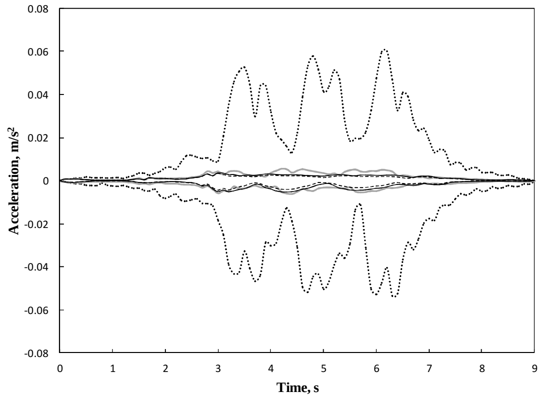


**Fig. 11.** Schematic acceleration response in a node located at 2 m from a sheet piling trench: ........, 0.5 m deep; ———, 1 m deep; – – –, 1.5 m deep; ———, 2 m deep

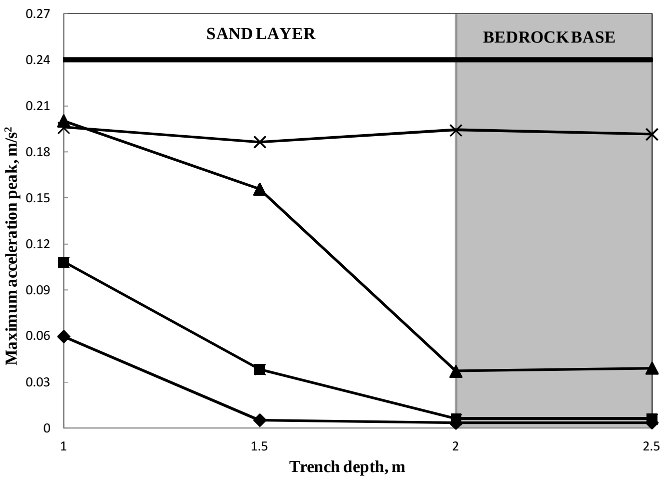


**Fig. 12.** Maximum acceleration peaks on a node located at 2 m from the trench: ———, no trench located; **X**, polyurethane in-filled trench; ▲, concrete in-filled trench; ■, open trench; ◆, sheet piling trench

Results in figure 12 imply the following:

- Generally speaking, all the considered trenches have achieved some kind of vibration reduction level since all of them provide a mechanical discontinuity in the soil. Additionally, in every case vibration reduction keeps constant for depths above the sand thickness.
- Void trenches are the better ones since for every depth their vibration reduction is higher than for the in-filled barriers.
- Between void trenches, the most effective ones are those which vertical walls are held up by a sheet pile because it is a more stable structure. However, for a depth equal to the sand layer thickness the vibration reduction provided by both of them is almost the same. Moreover, as mentioned before, for trench depths bigger than 1.5 m the isolation level of the sheet piling trench keeps constant.
- Since its reflection coefficient is smaller (see Table 4), a concrete in-filled trench is much more efficient than a polyurethane one. In contrast, for low depths, their effectiveness is similar. In fact, the concrete in-filled trenches isolation level has resulted to be very sensitive to depth.

From these ideas, two main conclusions have been reached:

- It has been clarified that void trenches are more effective than in-filled ones. It has been seen that for a depth equal to the sand layer thickness, the reduction level for both of them is similar. However, the sheet piling trench presents a better structural stability and a depth of 1.5 meters may be a suitable solution for the problem.
- It has been confirmed that the reflection coefficient is highly influent in the effectiveness of an in-filled trench. However, from figure 12 the next situations can be considered:

– If $c_{ij} < 1$, i.e. the material trench is stiffer than soil. Vibration reduction is achieved and a big reduction is provided if the coefficient is near zero.

– If $c_{ij} > 1$, i.e. the material trench is softer than soil. Vibration reduction is also achieved but not so much as in the previous situation since in the present case reflection phenomenon does not occur.

– If $c_{ij} = 1$, no vibration reduction is achieved since no discontinuity is located in the soil structure.

From that, it is well known that the best materials to be used for in-filled trenches are the stiffer ones as concrete is. In contrast, short concrete in-filled trenches have to be disposable. Their reduction level is similar to the polyurethane one which has the same magnitude order as the reference situation. With that, a 2 meters deep concrete in-filled trench may also be a suitable solution for the analyzed cross section since it provides an adequate vibration reduction and it has a very stable structure.

## 5. Conclusions

A finite element model for the prediction of railway ground vibration has been developed and validated with real data. For the analysis, the Rayleigh damping approach has been adopted. Wave transmission condition has been respected and the results are valid for a frequency range from 2 to 50 Hz. The modeled track has been subjected to quasi-static load and applied for the analysis of different configurations of wave soil barriers. From the presented results, the following conclusions can be drawn:

- Regarding the characteristics of a wave barrier and in ascending order of their influence on its effectiveness, the parameters which have been studied are: width, depth and barrier typology.
- The increase of the barrier width within sensible values for urban areas does not affect excessively the vibration isolation provided by a trench. In consequence, non dynamic but practical design criteria have been proposed to choose the trench width in this paper.
- An increase of the trench depth for a layered soil indicates clear improvement of the isolation effect of the trench. Moreover, the optimum depth which provides the maximum isolation is given when the trench base is in contact with the surface bedrock base. No more depth is needed since the trench effectiveness will not increase.
- Dense and stiff materials are the most suitable ones to be used for an in-filled trench since their function is based on the reflection of the surface Rayleigh waves.
- Open trenches are more effective than in-filled ones. A sheet piling trench avoids suffering from instability problems which an open trench may have. Moreover, it has been found that a sheet piling trench does not need to reach the bedrock base to achieve the maximum vibration isolation.

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