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SOIL-STRUCTURE INTERACTION EFFECTS ON THE TRANSVERSE RESPONSE OF BEAM BRIDGES UNDER MOVING LOADS AND ITS APPLICATION TO RAILWAY TRAFFIC

Alejandro Doménech[1], Antonio Romero[2], María D. Martínez-Rodrigo[1]*, Pedro Galvín[2]

1: Mechanical Engineering and Construction Department
Universitat Jaume I
Avda. Sos Baynat s/n, Castellón 12006, Spain
e-mail: {domeneca, mrodrigo}@uji.es

2: Escuela Técnica Superior de Ingeniería
Universidad de Sevilla
Camino de los Descubrimientos, Sevilla 41092, Spain
e-mail: {aro,pedrogalvin}@us.es

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Abstract *This paper describes a research work on the dynamic behaviour of beams traversed by moving loads including soil-structure interaction effects. The main application of the study is the analysis of the transverse vibratory response of railway bridges, taking into account the interaction of the substructure with the soil when the super-structure may experience resonant conditions, and undergo considerably high levels of transverse accelerations. As this phenomenon is highly influenced by the free vibration response induced by each axle load, a numerical investigation is carried out analyzing the effects of the wave propagation problem on the free vibration response of beams under moving loads. To this end a coupled three-dimensional boundary element-finite element model formulated in the time domain is used to reproduce the soil and structural behaviour, respectively. A subset of bridges is defined considering span lengths ranging from 12.5 to 25 m, and fundamental frequencies covering existing deck typologies in this span length interval. As for the soil properties, a homogeneous half-space is considered with shear wave velocities ranging from 80 to 365 m/s. In these scenarios, preliminary conclusions are derived regarding the conditions of maximum free vibration and cancellation of the response under a moving force, and how these are affected by the soil properties. This information will be used in a second phase of the investigation to predict how the acceleration response of the bridge deck at resonance is modified by the soil conditions in the case of bridges traversed by trains of loads. In this paper the approach adopted is justified, a parametric analysis is designed and preliminary results are shown.*

1. INTRODUCTION

The dynamic response of beams under the circulation of moving systems has been a deeply investigated topic during the last decades [1]-[4], partly due its direct application to the problem of bridges subject to the action of travelling vehicles. In this regard, railway bridges have received special attention, as the periodic nature of axle loads may induce important vibration levels in the structures, particularly under resonant conditions [5]. Especially critical in this regard are short-to-medium span bridges composed by simply-supported decks with usually associated low masses (see Fig. 1), which may experience high levels of vertical accelerations at the deck level in these situations. This problem aggravates for low structural damping levels, typical in the aforementioned constructions [5]. Resonance in railway bridges may lead to adverse consequences such as ballast destabilization, general degradation of the track and a raise in the maintenance costs of the line.

Figure 1. Railway bridge in High Speed line composed by short simply supported bays.

Resonance in simply-supported beams or bridges takes place when the excitation period of the axles, i.e. the ratio between the characteristic distance or distance causing resonance and the train speed, is a multiple of one of the structure's natural periods. When this happens, the free vibration oscillations induced on the structure when each load abandons it accumulate, and the transverse response of the bridge progressively increases if the number of axles is sufficient. In short to medium span bridges with nowadays maximum train speeds, the characteristic distance associated with detrimental levels of transverse accelerations due to resonance usually corresponds to the length of the passengers' coaches. Therefore, the amplification of the transverse response of beams or bridges at resonance depends both on the periodicity of the loads and on the amplitude of the free vibrations left by every single load. This level of free vibrations for a particular load depends on the travelling speed and on the structure natural frequencies, and may become maximum for speeds of maximum free vibration or negligible, when the so-called cancellation phenomenon takes place [6].
The aforementioned free vibration levels of beams or bridges under moving loads, and their effect on the amplification or cancellation of resonance have been evaluated in the past considering simple models for the bridge structure: generally simply supported (S-S) beams

[4], [6], [7], elastically supported (E-S) beams [6], [8], and simply-supported or elastically supported plates [9] when the contribution of three-dimensional deformation modes of the deck needs to be considered. In all these studies, the soil-structure interaction (SSI) effect is neglected.

Only a few studies have investigated the resonant response of beams or bridges taking into account the effect of the waves transmitted through the soil from the substructure [10]-[12]. Some authors [10]-[11] suggest that the resonant response of a railway bridge could be considerably affected by the soil flexibility, leading to a reduction of the resonant speeds of circulation and of the transverse response amplitudes at the deck level due to the increase of damping. Others authors, nevertheless, indicate that for certain typologies the consideration of simply-supported conditions may provide non conservative results, when it comes to predicting the acceleration level. In the opinion of the authors of this contribution, there is a need to understand how the soil-structure interaction effects affects the free vibration response of beams, and the maximum free vibration and cancellation phenomena, which are the fundamental aspects governing resonance. Moreover, this study should be carried out considering different bridge lengths and deck typologies in order to be able to obtain general trends and conclusions. The present contribution, describes the parametric investigation that the authors are nowadays developing in this context.

2. NUMERICAL SSI FORMULATION AND IMPLEMENTED MODEL

2.1. Fundamental hypotheses of the SSI formulation used

In the research line that is being developed by the authors, soil-structure interaction effects in beams and bridges traversed by moving loads, is evaluated using a coupled three-dimensional Finite Element-Boundary Element model (FEM-BEM) in the time domain implemented in the SSIFiBo toolbox developed by Galvín et al. [13]. SSI analyses are carried out by domain decomposition in two subdomains. Soil behaviour is represented by the BEM, while structures are modelled with the FEM. Coupling of BEM and FEM equations is carried out by imposing equilibrium and compatibility conditions at the soil-structure interface. Both systems of equations are assembled into a single global system, together with the equilibrium and compatibility equations [10]. The BEM is based on a time marching procedure to obtain the time variation of the boundary unknowns, i.e. displacements and tractions. Piecewise constant time interpolation functions are used for tractions and piecewise linear functions for displacements. The fundamental solution for the displacement and traction response is evaluated analytically, and nine node rectangular quadratic elements are used for spatial discretization. Expressions of the fundamental solution for displacements and tractions due to an impulse point load in a three dimensional elastic full-space are included in [14]. An approach based on the idea of using a linear combination of equations for several time steps in order to advance one step is used to ensure that the stepping procedure is stable in time. After boundary unknowns are solved, the scattered wave field at any internal point is computed by means of the integral representation of Somigliana identity.

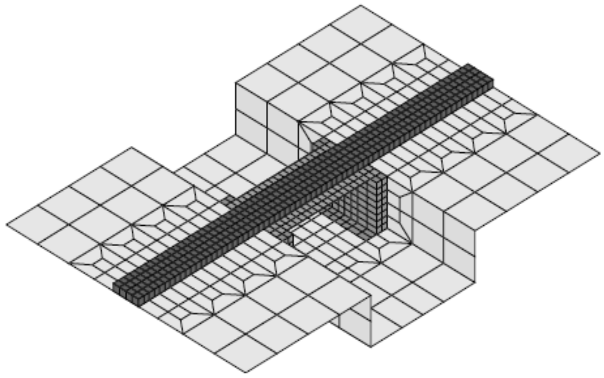

Figure 2. Discretization example of a coupled BEM-FEM for soil-structure interaction analysis.

2.2. Implemented model for analysis

The objective of the investigation is to evaluate the SSI effects on the free vibration response of beams traversed by a single moving load once the load has left the structure. This is related with the amplification of resonance and cancellation of resonance that may occur when the beam is subjected to trains of equidistant loads. Museros et al. [6] investigated this phenomenon solving the analytical conditions for maximum free vibration response and cancellation in simply-supported and elastically supported beams (Fig. 3b,c) and stated that these conditions, when coincide with resonant velocities, provoke very relevant resonant amplifications or almost inexistent resonant situations. Due to the importance of the free vibration amplitudes in the resonant response of beams and bridges, the model represented in Fig. 3a is investigated herein.

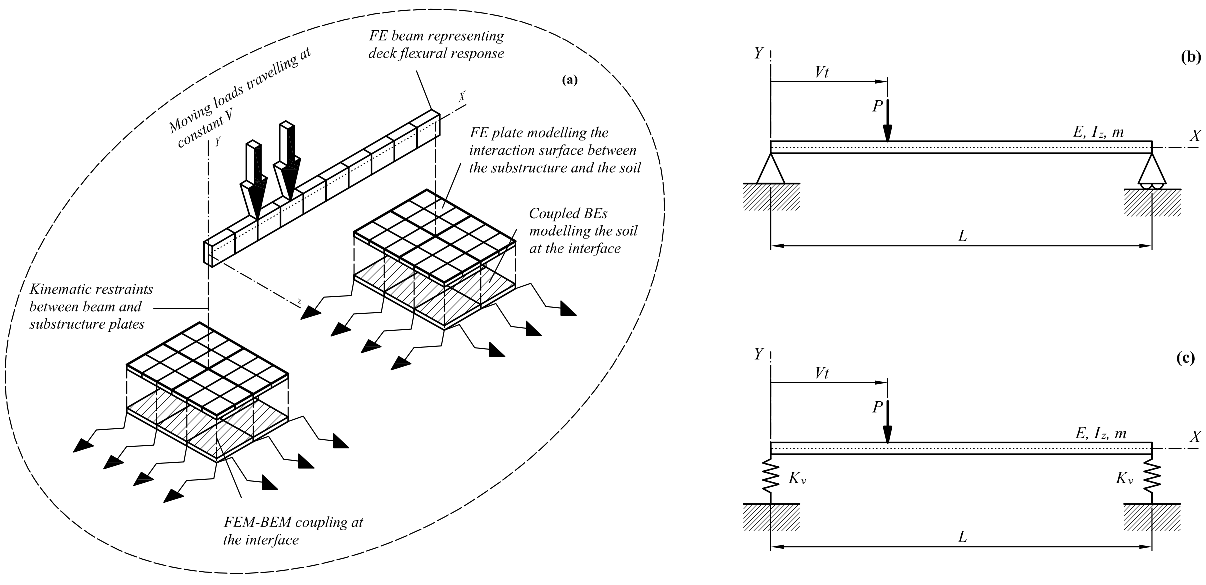

Figure 3. (a) Schematic representation of the model under analysis. (b) and (c) simply supported and elastically supported beam under travelling load.

3. PARAMETRIC ANALYSIS

In order to be able to derive general conclusions applicable to different bridge lengths, deck typologies, soil properties and circulating velocities, an extensive parametric numerical study is designed. Beams of lengths ranging from 12.5 to 25 m in increments of length of 2.5 m are considered. For each length, three theoretical fundamental frequencies, covering the Eurocode 1 frequency range for dynamic simplified analysis [14] of simply-supported railway bridges (see Fig. 4), are selected. Beam masses have been defined in order to represent realistic deck typologies found in conventional and High-Speed lines structures, after the studies from [14]. Regarding the soil properties, three single layer soil types are considered for each bridge with flexibilities covering the AASHTO classification [16], in particular with *s* and *p*-wave velocities of c_s={365, 220, 150} m/s and $c_p=2c_s$. Soil density has been considered equal to 1800 kg/m^3. Regarding structural damping, in a first approach the study is performed without structural damping and with 1% damping assigned to the first and third modes of the beam. Damping levels of 0%, 2%, 4% and 6% are evaluated for the soil. Eliminating damping, both in the structure and the soil, permits a better comparison of cancellation conditions with the analytical solution of the elastically supported beam.

Two types of analyses are performed for all the bridge-soil combinations under study: identification of fundamental frequencies and dynamic time-history analysis under the circulation of an axle load travelling at constant speed. The circulating velocities of the load are included in the following interval, expressed in terms of the non-dimensional speed parameter K_1 associated to the fundamental mode:

$$K_1 = \frac{V\pi}{L\omega_0} \in [0.1, 0.5] \tag{1}$$

where ω_0 is the fundamental frequency of the beam. The 0.5 limit is above the highest speeds that can be reached nowadays with existing rolling stock and railway infrastructures.

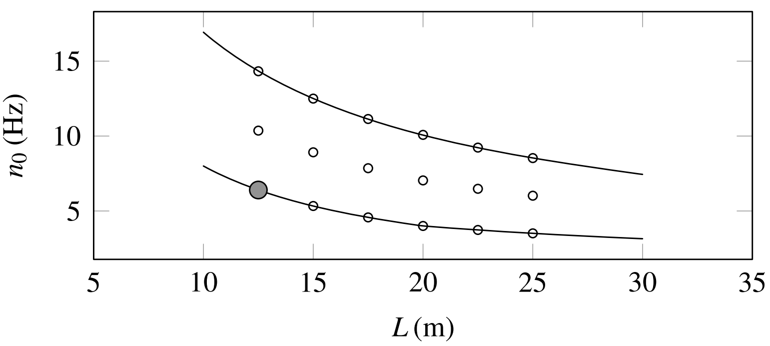

Figure 4. Span lengths and fundamental frequencies of the bridges under study. Eurocode 1 [14] lower and upper frequency limits for simplified dynamic analysis.

4. PRELIMINARY RESULTS

4.1. Natural frequencies of the bridges under study

First the fundamental natural frequencies of the bridges under study have been identified from the response under impulse loading. Fig. 5 shows the evolution of the frequencies with the soil flexibility. In the vertical axis the fundamental frequency computed considering SSI has been divided by that of the infinitely rigid soil (S-S case). The analyses have been performed considering 1% damping in the structure and 2% in the soil. In the plot, three lengths are included (12.5, 17.5 and 25 m) for the sake of clarity, as intermediate values present a monotonic behaviour.

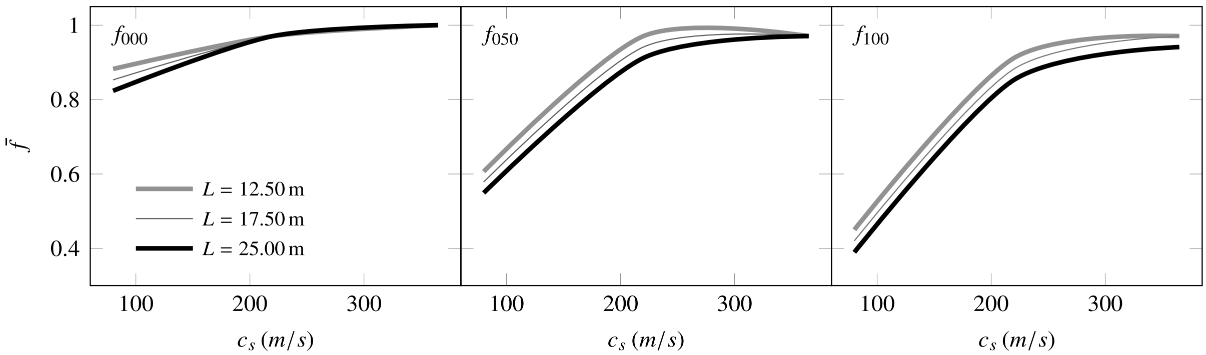

Figure 5. Evolution of fundamental frequencies with soil flexibility.

As c_s increases, and therefore the soil becomes stiffer, the fundamental frequency of the beams tends to the S-S one. The structures that are less affected by the soil flexibility are those with lower natural frequency for all the lengths (f000 stands for the lower frequency limit in figure 4). These beams fundamental frequency is reduced around 20% for the most flexible soils and the longest spans. Bridges with highest natural frequencies (f100, upper limit in Fig. 4) are most affected by the SSI effects, experiencing maximum reductions in the fundamental frequency that reach 50% in the softer soils. It must be clarified that c_s = 80 m/s, softest soil under consideration, is a considerably soft soil, but it has been included in order to point out the interaction effect. These results are consistent with the frequency evolution included in [6] for the elastically supported beam. In this contribution it was shown that natural frequencies were more affected as the ratio between the supports flexibility and the structure flexural flexibility increased.

4.2. Maximum free vibration response under a moving load

In Fig. 6 the maximum transverse displacement, non-dimensionalized by the static deflection at the mid-span section, computed in the free vibration phase (once the load has left the beam) is represented. Fig. 6a shows the analytical solution for the elastically-supported beam (Fig. 3c), included in [6]. This response is associated to only the fundamental mode and κ is the ratio between the supports vertical flexibility and the beam flexural flexibility (κ=0 corresponds to the simply-supported case). In Fig. 6b the dynamic response of the beam has been represented for one of the bridges under study including soil-structure interaction effects. The particular case is pointed out in Fig. 4. In this case, both the analytical E-S response and the numerical SSI case have been computed in the absence of damping in order to be able to visualize more clearly the evolution of the cancellation conditions.

From the analysis of Fig. 6 several aspects should be pointed out: (i) when the SSI is taken into account velocities leading to maximum free vibration response and to cancellation sequentially take place, in the same way that occurs for the E-S beam; (ii) as c_s and c_p decrease, going from stiffer to softer soils, the cancellation non-dimensional velocities increase as in the E-S case; (iii) in the plot, depending on the non-dimensional speed interval, the maximum free vibration response may be associated to stiffer or softer soils; (iv) even though for the SSI problem the response is obtained with the full model, and it is not limited to the fundamental response, cancellation takes place at certain speeds and the response in free vibration practically vanishes.

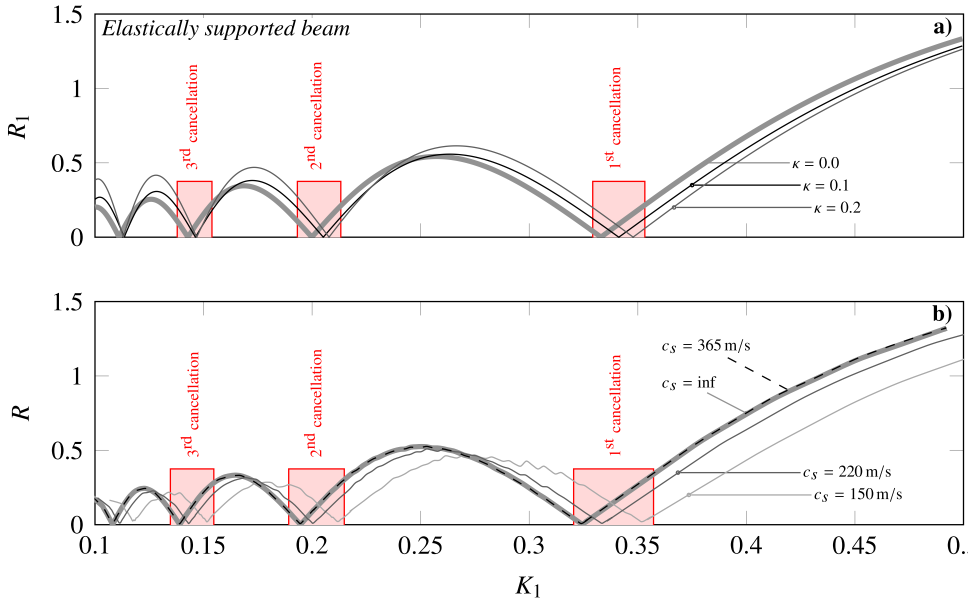

Figure 6. Maximum free vibration displacement response of (a) elastically-supported beam; and (b) L=12.5 m, f_1=6.4 Hz under a constant moving force including SSI (m_b=12500 kg/m, ζ_b=0, ζ_s=0).

The relevance of these analyses is that in the case of resonance induced on the bridge or beam by repetitive forces, depending on if the resonant velocity is close to a cancellation speed or to a maximum free vibration condition, the amplification drastically reduces and the resonant situation may even not take place at all, or the amplification of the response at resonance may be substantial, respectively. Also, depending on the non-dimensional speed at which resonance takes place, it is possible to predict what type of soil may lead to a higher amplification of the structural response.

5. CONCLUSIONS

In the present contribution, the dynamic response of beams travelled by moving loads is analyzed taking into account soil-structure interaction effects. The main practical application of the study is the analysis of the transverse vibrations of simply-supported railway bridges considering short to medium span lengths. These types of structures may experience excessively high levels of transverse accelerations at the deck level under resonant conditions. To the authors' knowledge extensive studies on the basic mechanisms that govern the resonant and cancellation response of beams or bridges, taking into account the effect of soil-structure interaction, have not been performed and could lead to a better understanding of the dynamic behaviour of real structures. In this context a three-dimensional finite element boundary element coupled model in the time domain is used to simulate the dynamic response of beams traversed by moving loads. A parametric analysis is defined covering lengths from 12.5 to 25 m and natural frequencies representing different railway deck typologies. Three different types of single-layer soils are evaluated for each structure.

In a first approach, the fundamental frequencies of all the bridges under study are identified from the response under impulse loading. Secondly, the maximum response of the beams is obtained in the free vibration phase right after a single travelling load has crossed the structure. A wide range of circulating velocities is defined and envelopes of maximum response are obtained and analysed.

From the preliminary results it is concluded that the fundamental frequency of the structures tends to the S-S one as the soil stiffness increases. The structures that are most affected by the soil flexibility are those with highest natural frequency for all the lengths. These results are consistent with the frequency evolution included in [6] for the elastically supported beam. Regarding the analysis of maximum free vibration under the circulation of single loads, it is concluded that: (i) when the SSI is taken into account velocities leading to maximum free vibration response and to cancellation sequentially take place, in the same way that occurs for the E-S beam; (ii) as c_s and c_p decrease, going from stiffer to softer soils, the cancellation non-dimensional velocities increase as in the E-S case; (iii) in the plot, depending on the non-dimensional speed interval, the maximum free vibration response may be associated to stiffer or softer soils; (iv) even though for the SSI problem the response is obtained with the full model, and is not limited to the fundamental modal response, cancellation takes place at certain speeds and the response in free vibration practically vanishes. The results from this parametric study will used in a second phase of the investigation to predict how the acceleration response of bridge decks at resonance is modified by the soil properties when railway traffic is considered.

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