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Effect of soil properties on the dynamic response of simply-supported bridges under railway traffic through coupled boundary element-finite element analyses

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A B S T R A C T

Railway induced vibrations on short-to-medium span simply-supported (SS) bridges is addressed in this contribution. Such structures may experience high levels of vertical acceleration at the platform, leading to adverse consequences such as a premature degradation of the ballast layer and passenger discomfort. In the present study, the evolution of the bridge dynamic response when soil-structure interaction (SSI) is taken into account is investigated. To this end a coupled three-dimensional (3D) Boundary Element-Finite Element model (BEM-FEM) formulated in the time domain is implemented to reproduce the soil and structural behaviour, respectively. First, a set of soil-bridge systems of interest is defined, covering a wide range of lengths and natural frequencies for the structures, and an interval of expectable elastic properties and damping levels for the soil. Then, different types of analyses are performed on the soil-bridge systems extracting conclusions regarding the effect of including SSI in numerical models for predicting the bridge behaviour under railway traffic. In particular natural frequencies and modal damping levels are identified, and the structure amplification after the passage of a moving load in free vibration is investigated. Conclusions regarding how resonance and cancellation conditions may be affected by soil properties are extracted. Finally, the dynamic response of a real bridge, belonging to the Spanish railway network, is evaluated under the circulation of trains that induce second and third resonances of the bridge fundamental mode. The effect of the soil flexibility, soil material damping and the bridge resonance order are evaluated. Conclusions regarding the appropriateness of the results provided by common models which do not include SSI effects are extracted.

1. Introduction

The development of modern, efficient and operational transport systems is essential for a sustainable economic development. In this context the construction of new High-Speed railway lines and upgrading of conventional lines for higher operating speeds, has become a trend in Asian and European countries in the last decades. Railway infrastructures and, in particular, railway bridges, are expected to exhibit an adequate performance under these new traffic requirements guaranteeing traffic safety, passengers comfort, structural integrity and acceptable environmental conditions in terms of sound and vibration transmitted amplitudes.

The level of vibrations induced on bridges due to the circulation of railway convoys has become an issue of concern among the scientific and engineering community, due to the periodic nature of the vehicles axles and the operating speeds approaching and exceeding 300 km/h in many lines. The periodic nature of the axle transmitted forces may excite important transverse vibration levels in the structures, particularly under resonant conditions [1,2]. Especially critical in this regard are short-to-medium span bridges composed by SS decks with usually associated low masses. This problem aggravates for low structural damping levels, typical in the aforementioned constructions [1]. Fig. 1 shows two examples of such structures, belonging to the Spanish railway network, with decks composed by concrete slabs resting on series of pre-stressed concrete girders. Even though this typology is not common in High-Speed lines of new construction, due to its poor dynamic performance [3], these beam-type bridges do exist in former conventional lines upgraded for High-Speed.

Resonance in railway bridges may lead to adverse consequences such as ballast destabilization, passenger discomfort, a general degradation of the track and a raise in the maintenance costs of the line [1,4]. For this reason, according to standards, the maximum deck

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Fig. 1. Railway bridges in Spanish lines composed by simply-supported bays of short-to-medium span.

acceleration must be checked at the Serviceability Limit State for the prevention of track instability, and regarded as a traffic safety requirement [5].

Resonance takes place when the excitation period of the axles, *i.e.,* the ratio between a characteristic, or many times repeated, distance and the train speed is a multiple of one natural period of the structure. When this occurs, the free vibration oscillations induced by every load accumulate, and the transverse response of the bridge progressively increases, leading to a substantial amplification 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 dynamic amplification 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. Under ideal SS conditions and in the absence of damping, the amplification of the free vibrations left by every load depends on the ratio between the structural periods and the travelling time of the load. As indicated in [6], depending on this ratio the beam may experience substantial levels of free vibrations (maximum free vibrations) or these may practically cancel (cancellation of free vibrations).

If the limits on the bridge deck acceleration cannot be met in an existing structure, strengthening measures may be applied in order to modify its dynamic properties and, consequently, its dynamic behaviour [7]. Passive control techniques could also provide cost-effective solutions increasing the overall damping levels of the structure and reducing the deck vibrational response at resonance [8]. In either case of new or existing structures, it is essential to develop accurate numerical models, able to realistically predict the vibration levels for the expected traffic conditions in order to make the best decision in the design stage or when a line is upgraded for higher operating speeds. According to some authors [9], the choice of boundary conditions for dynamic analyses appears to constitute a group of very sensitive parameters which have a considerable influence on the dynamic response of certain bridge types.

The phenomena of resonance and cancellation experienced by beams or bridges under the circulation of moving loads has been studied by several researchers [6,10–17]. Nevertheless in the previous works, soil-structure interaction is always disregarded and classical boundary conditions are assumed for the bridge deck. According to some authors, in certain soil environments an increase in the fundamental natural periods of moderately flexible structures due to SSI may have a detrimental effect on the structural behaviour [18]. The work presented herein arises in this context.

Only a few authors have investigated the dynamic response of beams or bridges and, in particular, the conditions of resonance and cancellation phenomena taking into account the wave propagation in the soil. Lu et al. [19] prove numerically the occurrence of resonance and cancellation in a periodic viaduct subject to moving loads considering pile-soil-structure interaction. Wu and Yang [20] apply a semi-analytical approach to analyse ground vibrations induced by trains moving over elevated bridges. The authors use impedance functions to represent the foundation-soil interaction and an elastic half space model for the soil wave propagation problem. In [21,22] the authors investigate ground vibrations induced by High-Speed trains crossing continuous girder bridges and rigid-frame viaducts, respectively. In both contributions the ground response is calculated by applying reaction forces on a 3D FEM with artificial viscous boundaries. Takemiya and Bian [23] investigate numerically the waves generated in the soil near a Japanese Shinkansen multi-span viaduct. The authors also present field tests measurements on the foundations and in the ground far field, showing frequency contents related to train axle distances and structure natural periods. In [9] Ülker-Kaustell et al. present a qualitative analysis of the dynamic SSI phenomenon on a portal frame railway bridge based on dynamic stiffness functions. The authors conclude that the contribution of the coupled soil-bridge system to the modal damping ratios is substantial, especially for the lower range of the soil elastic modulus.

Most of the previous works focus on the level of vibrations transmitted through the soil along the track, rather than on the bridge behaviour itself. In the opinion of the authors of this contribution, there is a need to investigate how soil properties, in terms of flexibility and material damping, may affect the dynamic response of short SS bridges susceptible to experience excessive accelerations at the deck level. If this kind of analysis is performed with generality, *i.e.,* considering expectable ranges of variation of structural and soil properties, interesting conclusions could be extracted regarding the appropriateness of the numerical models usually used by engineers when it comes to assess the performance of new structures, or that of existing structures subjected to more demanding operating conditions. In this study the authors complete the investigation initiated in Ref. [24], extending the analysis to several soil types with different levels of material damping, and particularizing the conclusions extracted to the case of a real structure.

In what follows a comprehensive ensemble of soil-bridge systems is defined covering typical lengths and structural typologies of short to medium span SS railway bridges, and a wide range of variation of soil flexibilities and material damping values. A sensitivity analysis is conducted on this ensemble and the evolution of the bridges natural frequencies and structural damping levels is evaluated with the properties of the soil. The amplification of the bridge dynamic response in free vibration under a single moving load (SML) is then presented, and, based on this analysis, conclusions regarding the evolution of the