Engineering Structures 172 (2018) 1025–1041

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

A vibration prediction model for culvert-type railroad underpasses

Manuel F. Báez H., Alberto Fraile*, Javier Fernández, Lutz Hermanns

Universidad Politécnica de Madrid (UPM), Spain

ABSTRACT

Although underpasses are low-cost solutions widely used in high-speed railway lines, their dynamic analysis is complex given the large number of variables involved in the problem and the high computational cost of detailed 3D models.

The objective of this study is therefore to present a simple and fast 3D method for estimating the dynamic behavior of culvert-type underpasses subjected to dynamic loads induced by high speed trains under normal operating conditions. This model was adjusted to data gathered *in situ* during a measurement campaign on the high-speed line between Segovia and Valladolid in Spain.

The prediction method is based on a sub-structuring approach with three key ingredients: an emission 2D finite element model that simulates the track; a slab model based on Kirchhoff theory and the Rayleigh-Ritz method using trigonometric shape functions; and sidewall-models using a formulation of a finite-length beam on a viscoelastic foundation. The emission model estimates the contact forces for the slab using the vertical dynamic behavior of the railway track, and the slab model accounts for the contribution of the soil-structure interaction that takes place at the sidewalls by means of the frequency-dependent stiffness at the corresponding joints.

1. Introduction

Underpasses or culverts are often used as wildlife corridors, water distribution structures or vehicular or pedestrian crossings in both conventional and high-speed lines (HSLs). Indeed, these solutions have been used since the 1800s. Initial studies in this regard were carried out by Willis [1], Stokes [2], and later, in the 1900s, by Kryloff [3], Timoshenko [4] and others. From the middle of the last century, more complex contributions were published by Hillgerborg [5], Biggs [6], Fryba [7] and later by Klasztorny and Langer [8]. As short-span bridges are sensitive to accelerations, they are designed to take advantage of the damping provided by backfills, which reduces the structural response, as described by Museros et al. [9].

Underpasses are important in railway lines as they form part of lifelines, therefore their correct functioning is crucial. Despite this, they have not been studied to the same extent as larger structures, such as bridges. This lack of studies may be attributed to the lower construction costs in comparison with railway bridges. In addition, numerous variables that can complicate their study need to be taken into consideration. For instance, train loads depend on train types, configuration, travel speed, track quality, and the railway track itself is a combination of a formation layer, ballast, sleepers, rails and fastenings. Moreover, there are a number of important interactions between the track and the culvert, as well as between the sidewalls and the backfill (i.e. soil-structure interactions).

In this regard, although 3D Finite Element (FE) [10,11] or Boundary Element models can be implemented [12], the number of elements needed for an adequate discretization of the structure and the surrounding soil is usually quite large. Additionally, the computational costs of performing transient dynamic analyses are high because a time-step size of at least 10^{-3} s is needed to adequately resolve the most important structural modes. For example, a 200 m-long high-speed train travelling at 160 km/h requires a simulation time of around 10 s. As a result, a single simulation involves 10,000 time-steps. As a certain speed range must be covered, the study of a culvert design usually requires 50 simulations per train type. It is therefore clear the influence of CPU computing time in the realization of the sensitivity analyses, usually performed in the design phase.

Different approaches, such as the use of 2D models like those described in [10] and [13], or the limitation of 3D models on culvert structure [14,15] (i.e. the surrounding soil is modeled as a combination of springs and dampers rather than as a continuum), can be used to reduce the computation time. However, although all these approaches help to reduce the computational time, this comes at the cost of not being able to capture all types of interactions that exist.

In this study, a 3D model that follows a sub-structuring approach which decomposes the system into emission, slab and wall sub-models is proposed. As the emission is independent of the other two, any track model can be used, thus meaning that existing tools can be easily

* Corresponding author at: Calle de José Gutiérrez Abascal, 2, 28006 Madrid, Universidad Politécnica de Madrid (UPM), ETSII, Estructuras/CEMIM, Spain.
E-mail addresses: mf.baez@alumnos.upm.es (M.F. Báez H.), alberto.fraile@upm.es (A. Fraile), jfernandezm@etsii.upm.es (J. Fernández), lutz.hermanns@upm.es (L. Hermanns).

https://doi.org/10.1016/j.engstruct.2018.06.025
Received 28 July 2017; Received in revised form 5 June 2018; Accepted 6 June 2018
0141-0296/

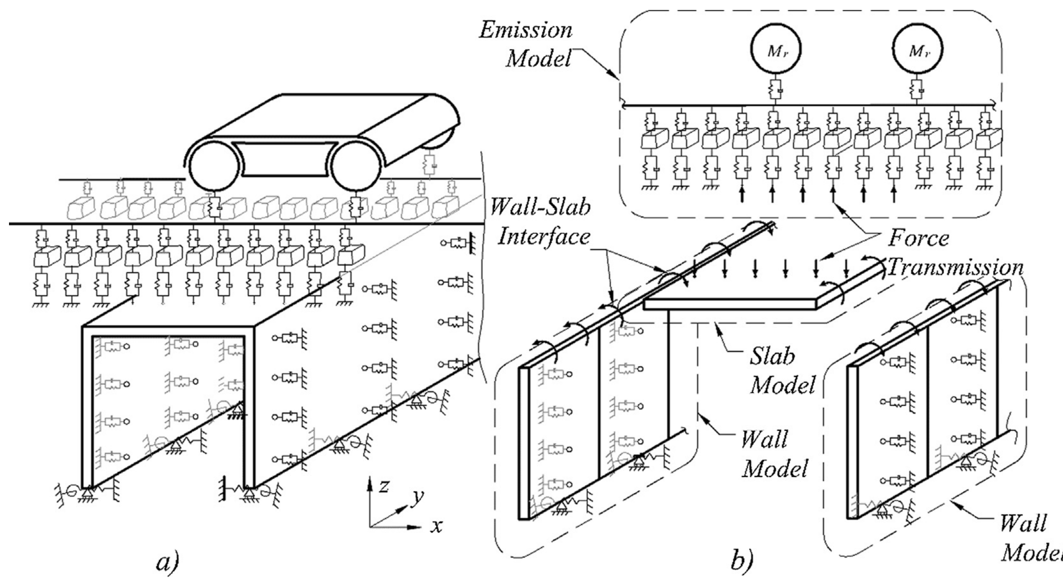

Fig. 1. (a) Structural representation. (b) Model decomposition.

combined with the slab and wall sub-models. Although this independency adds flexibility to the approach, the lack of interaction with the slab is an inherent limitation. The slab model is based on the Rayleigh-Ritz method applied to the Kirchhoff theory of plates using trigonometrical shape functions, and the side walls are considered as beams on a viscoelastic foundation. The slab-wall connection is ensured by imposing equilibrium and compatibility conditions at each shared degree of freedom (DOF).

The model was calibrated using data from measurements on a box culvert on the high-speed rail line between Valladolid and Segovia in Spain, where different types of high-speed trains travel at speeds of between 200 and 300 km/h.

2. Numerical model

The numerical model uses a sub-structuring approach to estimate the dynamic behavior of the structure. The general model has three components, namely emission, slab and sidewalls (see Fig. 1).

Fig. 1 shows a structural representation and its model decomposition. The vertical lines of the sidewalls in Fig. 1b indicate that the walls are modeled as several adjacent beams on a viscoelastic foundation. The deformation compatibility of two adjacent beams is not guaranteed along these lines as each element is connected to a different slab-based DOF. Nevertheless, this approach allows the contributions of the sidewalls and the backfill to be considered in a relatively straightforward manner by deriving a frequency-dependent rotational spring stiffness that can be incorporated into the slab model. The structural response is then estimated by combining the excitation forces generated by the emission model with the frequency response functions (FRF) of the slab model. As can be seen in Fig. 1, neither parapets nor wingwalls are modeled.

The analysis is performed as follows:

1. The frequency-dependent stiffness contributions of side-walls and backfill are determined.
2. The mass and stiffness matrices are calculated for the slab and combined with the stiffness terms of step 1 to obtain the system matrices.
3. The excitation forces are computed using any emission model (simplified model for this paper).
4. The slab response is calculated by combining excitation forces with the FRF system obtained in step 2.
5. The response of the wall is calculated.

The main advantage of this method is the small amount of time required to run the model, which makes it a good candidate for sensitivity analyses. Furthermore, steps 1 to 3 may be executed simultaneously.

The sub-models are explained in the following sections in the order in which they appear in the analysis.

2.1. Wall model

The wall model is needed for steps 1 and 5. Both the sidewalls and the backfill contribute to the rotational stiffness, which is added to the stiffness matrix of the slab.

The wall is considered as several vertical unit-wide beams on a viscoelastic foundation [16]. Each beam element is pinned at the upper end and attached at the bottom to lateral and rotational springs (Fig. 2).

The differential equation governing the motion of the wall is

$$EI\frac{d^4u}{dz^4} + \rho A\ddot{u} + k^*u = 0, \tag{1}$$

where u is the lateral displacement, E, I, A, ρ are the elastic modulus, second moment of area, area and density, respectively, and k^* is a viscoelastic foundation coefficient per unit area.

The viscoelastic foundation coefficient varies with frequency (ω) and corresponds to the Kelvin-Voigt model, which is represented by a viscous damper and elastic spring acting in parallel:

$$k^* = k + i\omega c, \tag{2}$$

where k and c are the stiffness and viscous damping coefficient of the spring per unit wall area, respectively.

The general solution to Eq. (1) is

$$u(z,\omega) = C_1\cos\left(\frac{\beta}{H}z\right) + C_2\sin\left(\frac{\beta}{H}z\right) + C_3\cosh\left(\frac{\beta}{H}z\right) + C_4\sinh\left(\frac{\beta}{H}z\right), \tag{3}$$

where C_1, C_2, C_3 and C_4 are to be determined from the boundary conditions and β is

$$\beta = \left(\frac{-k^*H^4 + \rho A\omega^2H^4}{EI}\right)^{\frac{1}{4}}. \tag{4}$$