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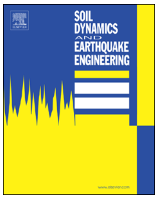

A power flow analysis of a double-deck circular tunnel embedded in a full-space

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ABSTRACT

The purpose of the present investigation is to obtain the mean power flow radiated by a double-deck circular tunnel and compares it to the one radiated by a simple circular tunnel. To achieve this, a harmonic line load is applied on the interior floor of the first one and at the bottom of the second one. For the double-deck tunnel, a new analytical model based on the receptance method is developed. The proposed model describes the dynamics of the interior floor using the thin plate theory and considers the Pipe in Pipe (PiP) model to describe the tunnel and soil coupled system. Plain strain conditions are assumed for both systems and conservative coupling is considered between them. Numerical results show significant differences between the power flow radiated by both tunnels, with the one radiated by the double-deck tunnel reaching much higher values. The effect of modifying the flexural rigidity of the interior floor is also presented.

1. Introduction

Society's concern about underground train-induced ground vibrations has been a growing issue over recent years. Because of the critical importance of this type of infrastructure in heavily populated cities, the need to have predictive tools to deal with the problem properly has arisen. The implementation of new tunnel geometries also presents new difficulties for the prediction of their vibration impact. This is the case, for example, of double-deck circular tunnels, where an interior floor divides the tunnel structure into two partitions and where trains or vehicles can usually travel through both of them. This infrastructure has already been constructed in some sections Line 9 of Barcelona's underground railway system.

For predicting the ground-borne vibration generated by underground trains, two principal types of model have been proposed: analytical models, which are fast but cannot deal with complex geometries, and numerical models, which can deal with them but with large computational and engineering costs. Andersen and Jones [1] presented a two dimensional and a three-dimensional (3D) Finite Element Method–Boundary Element Method (FEM–BEM) hybrid model of the problem and compared the results of both cases. They concluded, despite its computational cost, that 3D models are required to obtain accurate global results. To overcome this difficulty, Clouteau et al. [2] and also Degrande et al. [3] assumed the geometry of the tunnel–soil structure to be periodic in the train circulation direction and developed a 3D periodic FEM–BEM model which made use of the Floquet Transform to solve the whole problem by modelling only a reference cell of it. Gupta et al. [4] presented an experimental validation of the previous model. Using a similar approach, Sheng et al. [5] assumed invariance of the system in the same direction and were able to solve the complete problem in the wavenumber domain with a 2.5D FEM–BEM model.

Analytical and semianalytical models have also been developed for simple geometries of the problem. The most recognized of them is the PiP model proposed by Forrest and Hunt [6,7]. This model predicts the vibrations generated by a train moving along a circular tunnel considering the tunnel as a thin cylindrical shell surrounded by an infinite linear homogeneous elastic media. Hussein and Hunt [8] proposed a power flow study based on this model. The model was later improved by Hussein et al. [9] who replaced the initial full-space with a layered half-space. Kuo et al. [10] used it to study the effect of a second tunnel on the predicted vibration levels and by Jones et al. [11] to quantify the importance of voids in the tunnel–soil interface. Gupta et al. [12] compared the PiP model results with those obtained from a periodic FEM–BEM model, finding very good agreement between them. However the PiP model is a fast accurate tool for the prediction of underground train-induced ground vibrations, it assumes the tunnel as a cylindrical shell, being unable to deal with alternative construction geometries such as the previously mentioned case of Barcelona underground.

Coupled plate–cylindrical shell structures have been studied by several researchers because of its interest as airplane fuselage

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models. Peterson and Boyd [13] presented the first analytical model for a shell with a partitioned floor. Langley [14] studied, using a dynamic stiffness method, the free vibration of circular cylinders stiffened with an interior floor. With a variational formulation, Missaoui et al. [15] studied the free and forced vibration of a plate-shell system using artificial springs to simulate the structural coupling. Using the receptance method, Lee et al. [16] obtained the free vibrations of a simply supported shell-plate structure. The model was later extended by Lee et al. [17] to include the laminated composites case. For both cases, the free vibration of the subsystems was calculated using the Rayleigh–Ritz energy method and the eigenfrequencies of the global system thereby obtained were compared with experimental results. The receptance method was also used by Wang et al. [18] to study the power flow characteristics of the plate–cylindrical shell structure and by Zhao et al. [19] to study the forced response of a plate–cylindrical shell structure.

This paper studies the mean power flow radiated by a double-deck circular tunnel under the action of a harmonic line load. The proposed model, which is computationally much faster than any of the described numerical models, allows to obtain the radiation behavior of this new type of tunnel using an analytical approach. The considered approach is also ideal to investigate the effects of adding an interior floor in an underground tunnel. The results obtained are compared with the mean power flow radiated by a circular tunnel when the same type of load is applied. A comparison is made between the radiation patterns of both tunnels for the most important one-third octave bands in human exposure to building vibrations caused by underground trains [20].

2. Analytical formulation

In this work, the power floor radiated by a double-deck tunnel is compared to the one radiated by a simple tunnel. This comparison is performed considering that both structures are excited by a harmonic line load. This type of load is not adequate to calculate accurate values of the ground-borne vibration caused by a train passage but it is an interesting choice when a power flow comparison between two types of tunnel structures is desired. When harmonic line loads are considered, plain strain conditions are assumed and the problem is solved using only a cross-section of the tunnel–soil system.

Fig. 1 presents the cross-section of a double-deck tunnel model, with the chosen positive direction for the displacements (u_θ and u_r) and stresses ($\tau_{r\theta}$ and τ_{rr}) and the coupling condition considered between the tunnel and the interior floor. The cylindrical system of coordinates (θ, r) used to describe any point of the tunnel–soil system and the Cartesian system of coordinates (x_t, y_t) will be used to describe the mean local power flow distribution in Section 3. A harmonic line load f_4^p is applied vertically at Point 4 of the interior floor, which is assumed to be coupled to the tunnel at Points 1 and 2. The response of the described structure at Point 3 ((θ_3, r_3)) is obtained using the receptance method [21], which allows the receptance of a complex system to be calculated from the responses of its subsystems after assuming certain coupling conditions. In the case considered in this paper, the double-deck tunnel subsystems are the interior floor and the combined tunnel–soil system. The next subsections describe the dynamic model assumed for each of these parts and the coupling conditions considered.

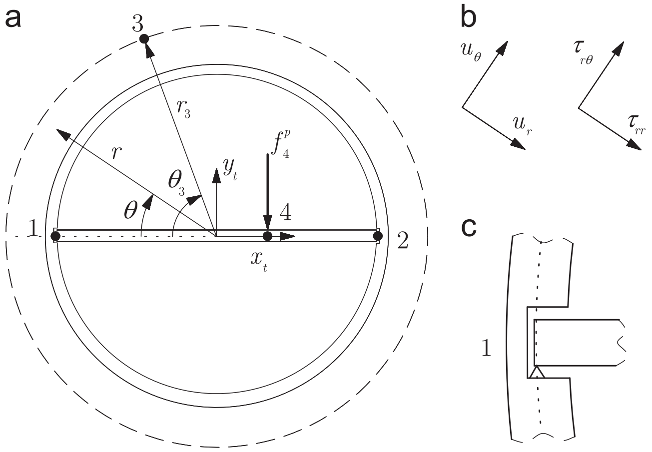

Fig. 1. (a) Cross-section of a double-deck circular tunnel. A Cartesian and a cylindrical system of coordinates are defined. (b) Positive signs for the displacements and stresses. (c) Coupling condition considered between the tunnel and the interior floor.

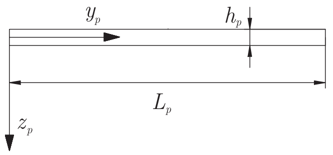

Fig. 2. Cross-section of the interior floor partition.

2.1. Interior floor formulation

The interior floor is considered to be a homogeneous isotropic strip plate of thickness h_p and width L_p with no prestressing effects acting on it. The ratio between the thickness and the width is assumed to be small enough to consider thin plate theory [22]. Fig. 2 presents a cross-section of the interior floor with its geometrical characteristics. The chosen system of coordinates is (y_p, z_p) and the deflection of any point of the plate is described by w_p. The equation of motion of a thin plate in plane-strain conditions is

$$D_p \frac{\partial^4 w_p(y_p, t)}{\partial y_p^4} + \rho_p h_p \frac{\partial^2 w_p(y_p, t)}{\partial t^2} = f_4^p(y_p, t), \tag{1}$$

where

$$D_p = \frac{E_p h_p^3}{12(1-\nu_p^2)}$$

is the flexural rigidity of the plate, ρ_p is its density, E_p is its Young modulus and ν_p is its Poisson's ratio.

The harmonic line load, which is considered unitary and to be applied at $y_p = y_4$, is written as

$$f_4^p(y, t) = \delta(y_p - y_4) \mathrm{e}^{\mathrm{i}\omega t}. \tag{2}$$

The deflection of the plate is assumed to be harmonic, so

$$w_p(y_p, t) = W_p(y_p) \mathrm{e}^{\mathrm{i}\omega t}. \tag{3}$$

Introducing Eqs. (3) and (2) into Eq. (1) the following equation is obtained:

$$\frac{\mathrm{d}^4 W_p}{\mathrm{d}y_p^4} - \kappa^4 W_p = \frac{\delta(y_p - y_4)}{D_p}, \tag{4}$$

where

$$\kappa = \sqrt[4]{\frac{\rho_p h_p \omega^2}{D_p}}. \tag{5}$$

The general solution of Eq. (4) is obtained using the modal participation method. Considering both edges free, the plain strain