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Numerical study of reduction in ground vibrations by using barriers

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ABSTRACT

Reduction in traffic-induced ground vibrations by the use of barriers is investigated. The traffic load characteristics were measured for motorway traffic. The effects of parameters on various types of barriers were examined by the use of a finite element model that was calibrated to green-field measurements. The model involved a layered soil and bedrock. The depth of a trench and the elastic modulus of a solid back-fill material were found to be the most important parameters to consider. In investigation of the effects of infiltration of water into an open trench, a coupled finite element formulation of the water and the soil was applied. Infiltration of water was found to decrease the achieved reduction. At long distances from the vibration source, of around 500 m and longer, amplification in vibration level can be seen when a trench has been installed. It was also found, at long distances, that the motion of the ground surface follows the motion of the bedrock.

1. Introduction

Occasionally, very strict vibrational requirements are specified for vibration-sensitive equipment used in high-tech facilities, such as large ground telescopes, radar towers and synchrotrons. High-tech facilities are often located in the vicinity of vibration sources of significant amplitude, such as trafficked roads and rail- and tramways. Traffic-induced ground vibrations can propagate to facilities nearby and lead to the vibration requirements for sensitive equipment being exceeded. It can be desirable in such cases to reduce the ground vibrations. The traffic-induced vibrations can be reduced by various means, such as shaping the landscape surrounding the facility or by placing a wave barrier in front of the facility [1,2].

Installing a wave barrier in the ground between a vibration source and a facility creates a discontinuity for the propagating waves. Waves that are incident to the trench give rise to different types of waves. These can be divided into five separate groups (see Fig. 1): (1) Rayleigh waves reflected back by the barrier, (2) Rayleigh waves transmitted through the barrier, (3) body waves from the barrier propagating downwards and back, (4) body waves from the barrier propagating forward and (5) waves propagating through the soil and the bedrock, under the barrier. Ground vibrations after the barrier has been passed are caused by (2), (4) and (5).

In the present paper, *barrier* is used as an umbrella term for various types of barriers. More specific, an empty barrier is referred to as a *trench*, a trench back-filled with a solid material is referred to as a *solid barrier*, and a trench infiltrated by water is simply referred to as a *water-infiltrated trench*.

1.1. Earlier studies

Since the pioneering work by Woods in 1968 [5], barriers used for reducing ground vibrations have been studied extensively. Several investigations of the effectiveness of wave barriers in terms of reduction in ground vibrations have been carried out, through field tests and numerical simulations by means of both the boundary element (BE) method and the finite element (FE) method, as well as combination of the two (FE–BE).

Extensive scaled field tests were performed in [5], in order to study the effectiveness of trenches, both close to the vibration source and at a considerable distance from it. On the basis of the experimental findings, certain guidelines concerning the dimensions of a trench to achieve maximal reduction in the ground vibrations are presented. It was also concluded that, because it is difficult to extrapolate full-scale tests from results of small-scale field tests, numerical investigations are of interest. Numerical studies of the effectiveness of barriers in terms of reduction in ground vibrations by means of the BE method have been carried out by, for example, [6–16]. The FE method is also extensively used in studies by, for example, [17–21]. Coupled FE–BE methods for studying the effectiveness of barriers in terms of reduction in ground vibrations have been employed by, for example, [22–26].

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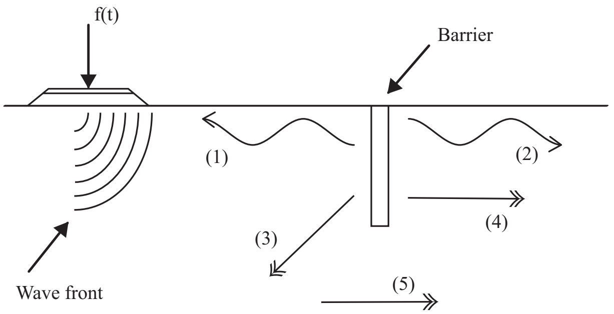

Fig. 1. Different waves stemming from waves incident to a barrier.

Some general conclusions from the numerical investigations are that trenches provide a more effective vibration isolation than soil barriers and that the depth of a trench being the one parameter that has the greatest effect on the effectiveness and the width could be negligible while the distance to the vibration source may be important to consider. Further conclusions are that the effectiveness of barriers depend upon the material parameters of the filling material and that barriers, as well as, sheet-pile walls and row of piles can be suitable for reducing ground vibrations. The use of a softer filling material increases the effectiveness of a solid barrier and also permits larger depths to be used than in the case of a trench, the depth of a solid barrier is more effective than increasing its width. Several studies, e.g. [20,24–27], also points out that the impedance mismatch, of the back-filling material and the surrounding ground, is the key factor of determine the efficiency of a barrier. Since the variation of the mass density, Poisson's ratio and the loss factor of the filling material is in practice small, at least compared to the elastic modulus, they were found to not appreciably affect the effectiveness of a solid barrier. Also, a concrete lid placed on top of a trench with double sheet-pile walls, for safety reasons, and the inclination of the trench were found to not affect the effectiveness to any marked extent.

1.2. Present study

The main objective of the study was to investigate the use of barriers for minimising traffic-induced vibrations. This was performed by establishing FE models, validated by green-field measurements, resulting in a model with a layered soil and bedrock able to predict the effectiveness of using a wave barrier. The characteristics of the applied traffic load was determined from vibrational measurements conducted at a motorway. Trenches, solid barriers and water-infiltrated trenches parallel to a motorway were studied. Installation of a wave barrier disturbs the wave front and reflects waves into the bedrock. Wavelengths being less attenuated in the bedrock than in the soil. Therefore, the reduction in ground vibrations at distances far from the barrier may be affected by the waves propagating under the barrier in the bedrock. Thus, the reduction obtained at distances far from the barrier was studied. The effects of infiltration of water into a trench were examined by employing a coupled FE model of the water and the soil, taking the interaction between them into account. Moreover, parametric studies of geometric parameters of a trench and studies of the material parameters of a filling material in a solid barrier were performed.

In the paper, the synchrotron facility, Max IV, serves as an example case. Fig. 2 presents an architectural sketch of the facility. It is built approximately 100 m from the motorway E22. An electron beam is to be controlled by a large number of magnets that are distributed along the ring-shaped building. Since the quality of the measurements obtained is dependent upon the vibration level of the magnets, very strict vibration requirements are specified. The vibration requirements regarding vertical displacements of the magnets are especially strict, its being required that these be less than 20–30 nm in root-mean-square (RMS) per second within a frequency span of 5–100 Hz.

2. Numerical calculations

In the section, the governing theory of structural dynamics and of fluid–structure interaction (FSI) are presented.

2.1. Structural dynamics

The differential equation of motion for the continuum formulation of a three-dimensional solid is written as

$$\tilde{\boldsymbol{\nabla}}^T \boldsymbol{\sigma}_S + \mathbf{b}_S = \rho_S \frac{\partial^2 \mathbf{u}}{\partial t^2} \tag{1}$$

where $\boldsymbol{\sigma}_S$ is the stress tensor, $\mathbf{b}_S$ is the body force vector, ρ_S is the mass density, $\mathbf{u}$ is the displacement vector, $\tilde{\boldsymbol{\nabla}}$ is a differential operator and t is the time. With use of Galerkin's method, the FE formulation for a structural domain becomes [28,29]

$$\mathbf{M}_s \ddot{\mathbf{u}} + \mathbf{K}_s \mathbf{u} = \mathbf{f}_s \tag{2}$$

where $\mathbf{M}_s$ is the mass matrix, $\mathbf{K}_s$ the stiffness matrix, $\mathbf{f}_s$ the load vector and $\mathbf{u}$ the nodal displacement vector. Since damping has to be included in the numerical model in order to obtain a realistic response, a rate-independent damping model was assumed since it provides a better match to the real behaviour of soils than other simple available damping models. A limitation of the assumed damping model is that it cannot be used in the time domain. Thus, the damping was described by a loss factor, introduced by the structural damping matrix [30].

2.2. Fluid–structure interaction

In order to investigate a trench infiltrated by water, FSI was considered. Two governing equations can be employed for describing the pressure field of a homogeneous acoustic fluid, which is assumed to be inviscid, irrotational (curl $\mathbf{u}_f = 0$), compressible and to undergo small pressure changes. The equation of motion, the volumetric drag being neglected here, can be written as

$$\rho_0 \frac{\partial^2 \mathbf{u}_f}{\partial t^2} + \boldsymbol{\nabla} p = 0 \tag{3}$$

where ρ_0 is the static density, $\mathbf{u}_f$ is the fluid displacement vector, t is the time, $\boldsymbol{\nabla}$ is the gradient operator and p is the acoustic fluid pressure [31,32]. The constitutive equation for a barotropic fluid with constant density can be written as

$$p = -c^2 \rho_0 \boldsymbol{\nabla} \mathbf{u}_f \tag{4}$$

where c is the speed of sound. With use of Eqs. (3) and (4), the wave equation for the acoustic fluid, the pressure serving as the field variable, can be written as the Helmholtz equation

$$\frac{\partial^2 p}{\partial t^2} - c^2 \boldsymbol{\nabla}^2 p = 0. \tag{5}$$

By expressing the pressure as a complex harmonic function

$$p = \hat{p} e^{i\omega t} \tag{6}$$

the wave equation in the frequency domain becomes

$$\boldsymbol{\nabla}^2 \hat{p} + \frac{\omega^2}{c^2} \hat{p} = 0. \tag{7}$$

Thus, with use of Galerkin's method, the FE formulation for the acoustic fluid domain can be written as