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Mitigation of ground vibration by double sheet-pile walls

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Abstract

Open trenches are an effective means of vibration mitigation, but they cannot be established in practice. When the trenches are covered by a concrete pavement, part of the efficiency may be lost. However, the present analysis indicates that barriers of this kind may still lead to a significant reduction of the horizontal and vertical vibrations caused by traffic at a nearby road or railway.

Keywords: *Dynamics; vibration screening; boundary elements; finite elements.*

1 Introduction

Ground vibration from railways and road traffic in the built environment are a nuisance to people and a potential source to damage on neighbouring structures. Wave barriers provide a means of reducing the vibrations, and such barriers may be constructed by double sheet-pile walls (Andersen and Liingaard, 2005). The aim is to maximise the impedance mismatch between the soil and the barrier, thereby reducing the transmission of waves through the barrier to a minimum. For this purpose, open trenches are effective, since the acoustic impedance of air is very low in comparison to the mechanical impedance of soil. In order to hinder percolating water from filling in the trenches, thereby losing the impedance mismatch between the barrier and the surrounding soil, gas cushions may be installed to form a sandwich structure as proposed by Massarsch (2005).

However, regarding the safety and comfort of pedestrians, it is necessary to cover the trench with a concrete lid, or pavement, when barriers are placed between a road or railway track and adjacent buildings. This provides a connection between the two sheet-pile walls, and as a result of this it may be speculated that the effect of the wave barrier is reduced significantly. This issue is treated in the paper, using a coupled boundary-element/finite-element model.

2 Computational model of the soil and the vibration barriers

The analysis of the wave propagation in the ground is performed in the frequency domain employing a two-dimensional coupled boundary-element/finite-element (BE/FE) model (Jones et. al, 1999). The soil is modelled by boundary elements, utilising the inherent ability of the method to radiate waves into an infinite domain. The track and the wave barrier are modelled by finite elements. Plane strain is assumed, i.e. the waves are induced by a line source that may to some extent represent a train. With no loads applied within the ground, the boundary-element (BE) part of the model is governed by Somigliana's identity,

$$C(\mathbf{x})U_i(\mathbf{x}, \omega) + \int_{\Gamma} P_{il}^*(\mathbf{x}, \omega; \mathbf{y})U_l(y, \omega) d\Gamma_y = \int_{\Gamma} U_{il}^*(\mathbf{x}, \omega; \mathbf{y})P_l(y, \omega) d\Gamma_y, \quad (1)$$

which relates the displacements $U_i(\mathbf{x}, \omega)$ to the tractions $P_i(\mathbf{x}, \omega)$ along the surface Γ of the soil domain. $U_{il}^*(\mathbf{x}, \omega; \mathbf{y})$ and $P_{il}^*(\mathbf{x}, \omega; \mathbf{y})$ are the Green's functions for the displacement and the traction, respectively. These describe the response at point \mathbf{x} in direction i to a point force, or displacement, varying harmonically with the circular frequency ω and unit amplitude, and applied at point \mathbf{y} in direction l . The scalar $C(\mathbf{x})$ depends solely on the surface geometry at the observation point \mathbf{x} . A derivation of Eq. (1) and the properties of $C(\mathbf{x})$ are given in Domínguez (1993).

The BE form of Eq. (1) is obtained by a discretization of the physical fields. The displacements and the tractions at the N_j nodes of boundary element j are stored in the vectors $\mathbf{P}_j(\omega)$ and $\mathbf{U}_j(\omega)$, and local quadratic interpolation is employed:

$$\mathbf{U}(\mathbf{x}, \omega) = \mathbf{\Phi}_j(\mathbf{x})\mathbf{U}_j(\omega), \quad \mathbf{P}(\mathbf{x}, \omega) = \mathbf{\Phi}_j(\mathbf{x})\mathbf{P}_j(\omega), \quad (2)$$

where $\mathbf{\Phi}_j(\mathbf{x})$ is a matrix storing the shape functions for each element. Inserting Eq. (2) into Eq. (1) leads to the matrix equation for the BE soil domain:

$$\mathbf{H}(\omega)\mathbf{U}(\omega) = \mathbf{G}(\omega)\mathbf{P}(\omega). \quad (3)$$

Component (i, k) of $\mathbf{H}(\omega)$ and $\mathbf{G}(\omega)$ stores the influence from degree-of-freedom k to degree-of-freedom i for the traction and the displacement, respectively, and the geometry constants $C(\mathbf{x})$ at each node are absorbed into the diagonal of $\mathbf{H}(\omega)$.

A transformation matrix \mathbf{T} is defined such that $\mathbf{F}(\omega) = \mathbf{T}\mathbf{P}(\omega)$. Here $\mathbf{F}(\omega)$ is the vector of nodal forces equivalent to the tractions $\mathbf{P}(\omega)$ applied on the soil domain. Subsequently, for each frequency $\mathbf{T}\mathbf{G}^{-1}(\omega)\mathbf{H}(\omega) = \mathbf{K}_{BE}(\omega)$ defines an equivalent dynamic stiffness matrix for the boundary element domain. This turns the BE domain into a macro finite element that can be assembled with the finite elements employed for the track and barrier structures. Hence, the solution is found as:

$$(-\mathbf{M}\omega^2 + i\mathbf{C} + \mathbf{K})\mathbf{U}(\omega) = \mathbf{F}(\omega). \quad (4)$$

Here, \mathbf{M} , \mathbf{C} and \mathbf{K} are the mass, damping and stiffness matrices, respectively, whereas $\mathbf{U}(\omega)$ and $\mathbf{F}(\omega)$ are the nodal displacements and forces, respectively. Finally, i is the imaginary unit, and it is noted that hysteretic damping is applied. Therefore, the material-dissipation term is independent of the frequency.

3 Parameter study of vibration barriers

The geometry of the track, soil and barrier is sketched in Figure 1, and material properties are listed in Table 1. In this study, the length of the sheet-pile walls is $l = 8$ m, the distance between them is $d = 2$ m, and the piles are modelled as 100 mm thick plates. For simplicity, the aircushions are modelled as an empty space. This is justified by the fact that the cushions have an insignificant shear stiffness and the impedance of the air inside is only slightly affected by a small increase in the pressure, i.e. $\rho_a c_A$ is in any case much smaller than $\rho_s c_P$, where ρ_a and ρ_s are the densities of air and soil, respectively, whereas c_A is the speed of acoustic waves in the air and c_P is the speed of dilatational waves in the ground. A harmonically varying force with unit amplitude is applied vertically on the concrete track, and the amplitudes of the horizontal and vertical displacements along the ground surface are suitably measured in dB,

$$\Delta_1 = 20 \log_{10}(U_1/V_0), \quad \Delta_2 = 20 \log_{10}(U_2/V_0). \quad (5)$$

V_0 is a reference value chosen as the amplitude of the vertical displacement at the centre of the track obtained at the frequency 10 Hz. With the definitions in Eq. (5), a decrease of 6 dB corresponds to a factor 0.5 in the response.

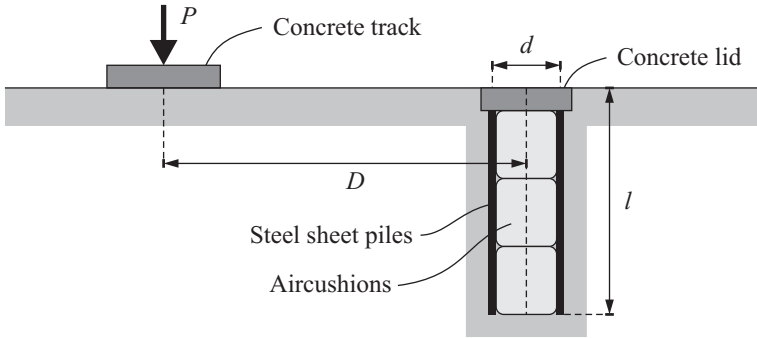


Figure 1. Geometry of the track and the wave barrier.

Results for the frequencies 20, 40, 60 and 80 Hz are given in Figures 2 to 5. The analysis is carried out for different distances, D , from the centre of the track to the centre of the wave barrier, and two situations are considered. In Figures 2 and 3, the trench is left open at the top, whereas the walls are connected by a concrete pavement in Figures 4 and 5.

Table 1. Material properties.

Material	Young's modulus, E (MPa)	Poisson's ratio, ν (-)	Density, ρ (kg/m ³)	Loss factor, η (-)
Soil	200	0.25	2000	0.05
Steel	200,000	0.30	7850	0.01
Concrete	20,000	0.15	2500	0.03

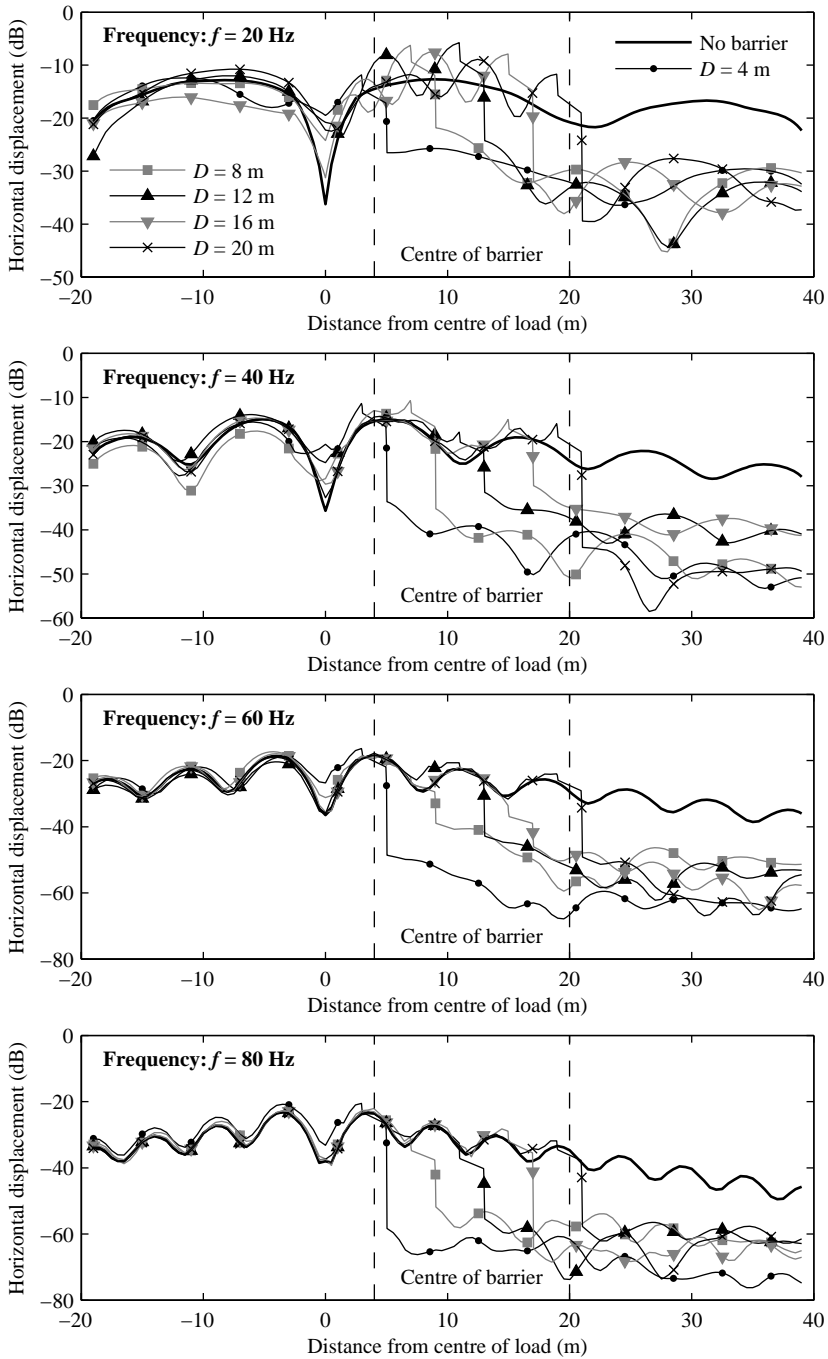


Figure 2. Horizontal displacement response (dB) along the ground surface for an *open* trench lined by sheet-pile walls and backfilled with aircushions.

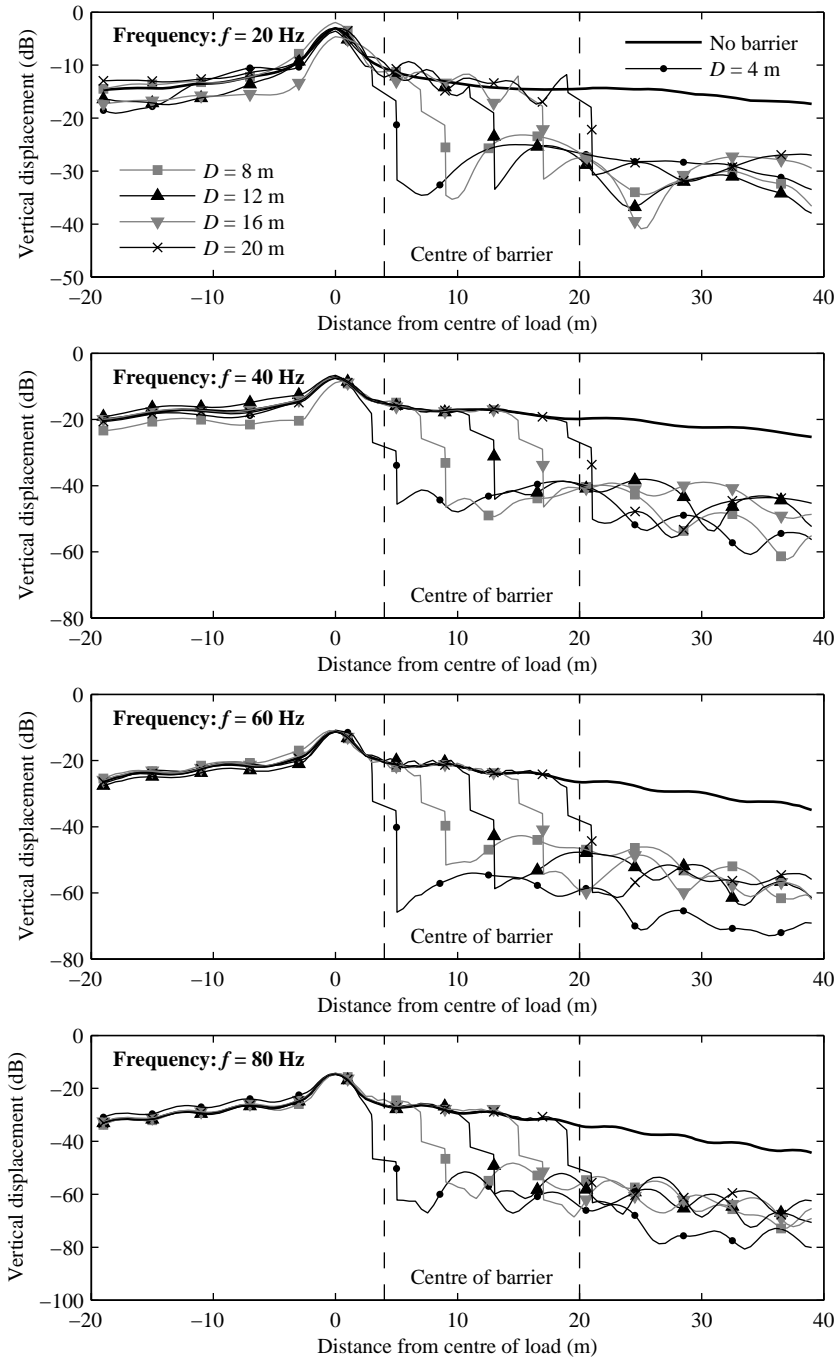


Figure 3. Vertical displacement response (dB) along the ground surface for an *open* trench lined sheet-pile walls and backfilled with aircushions.

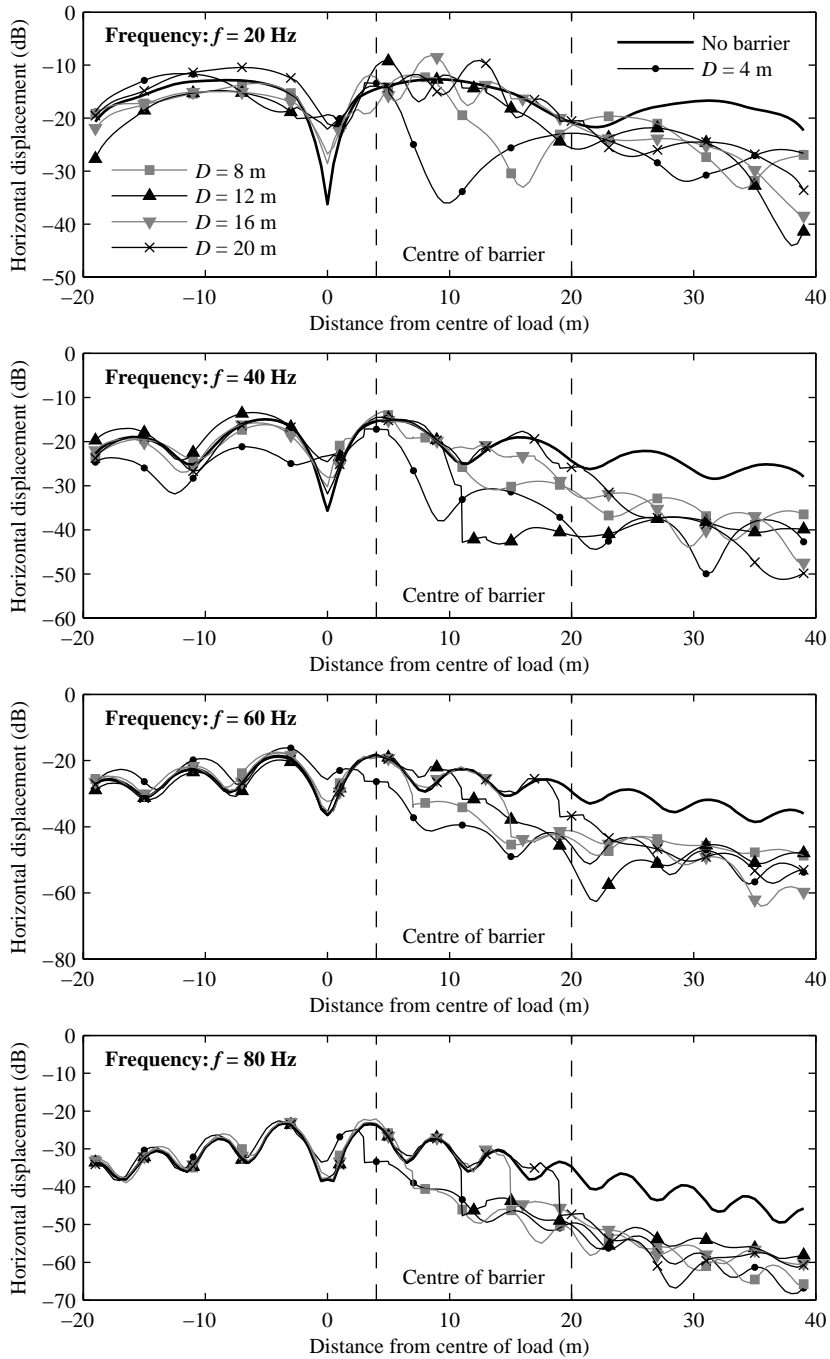


Figure 4. Horizontal displacement response (dB) along the ground surface for a closed trench lined by sheet-pile walls and backfilled with aircushions.

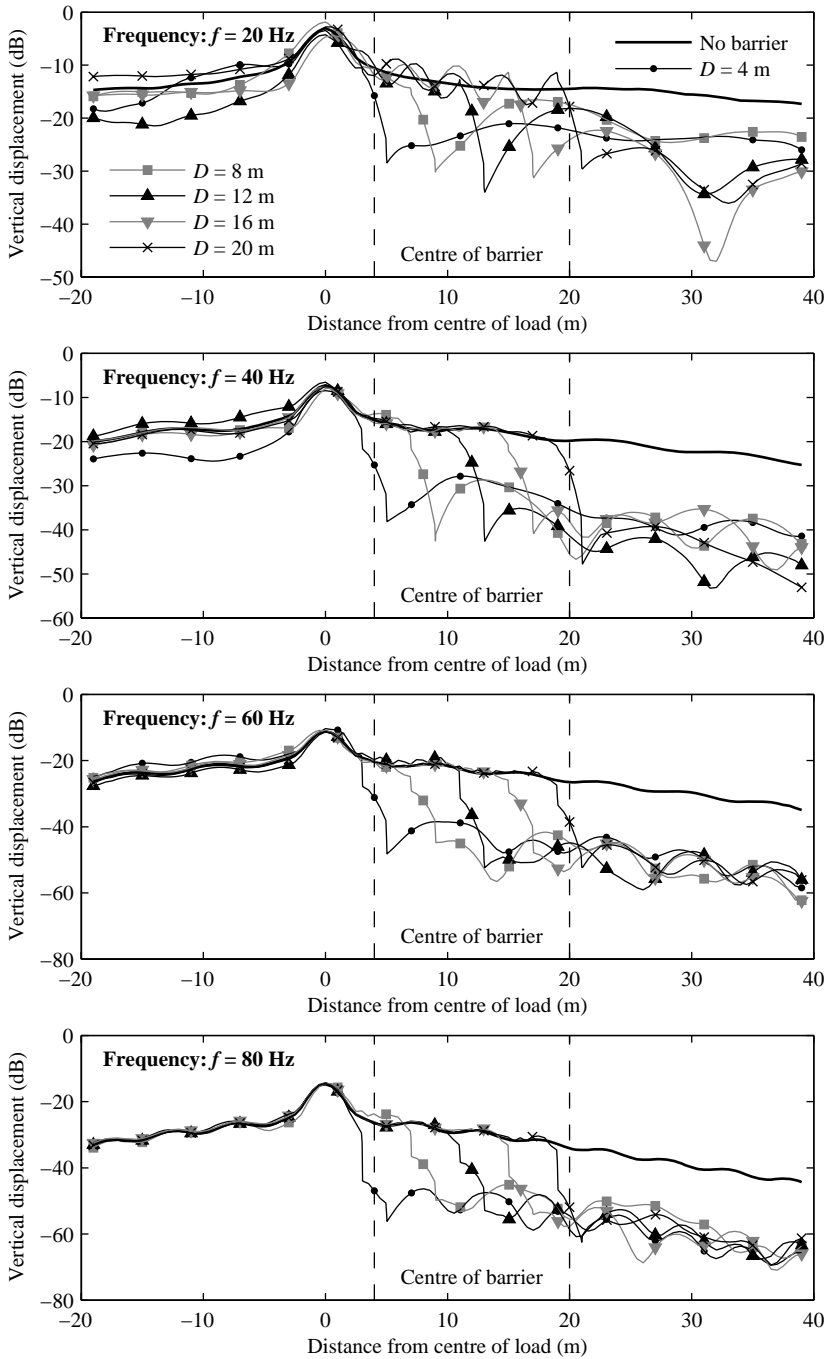


Figure 5. Vertical displacement response (dB) along the ground surface for a closed trench lined by sheet-pile walls and backfilled with air cushions.

From Figures 2 to 5 it is observed that the amplitudes of the vibration decrease with an increase in the frequency. This was to be expected, since the dynamic stiffness of the ground increases with the frequency. Further, the response is generally diminishing away from the track due to geometrical damping. Even when no barrier is present, a wavy nature of Δ_1 and in particular Δ_2 is noticed. The local tips and dips in the displacements arise due to the fact that the load acts on a concrete slab with a width of 2 m. If a point force was put directly on the ground, a monotone decrease in the displacement response would be recorded.

The barrier has a significant screening effect, independently of the distance, D , between the track and the trench and whether or not the lid is installed. For all frequencies, a reduction of about 10–20 dB is achieved compared to the situation without the barrier. When no pavement has been cast on top of the trench, the entire drop in vibration level occurs just outside the barrier (see Figures 2 and 4). In the case of vertical vibrations, this is also the case after the installation of the pavement, see Figure 5. However, concerning the horizontal vibrations it is observed that the major part of the reduction takes place at the wall on the inside of the barrier for most combinations of D and the frequency, cf. Figure 3.

Regarding the horizontal as well as the vertical response at frequencies beyond 20 Hz, $D = 4$ m is optimal when no lid is present. However, when the lid is installed, a longer distance between the track and the barrier may be preferred. In particular, $D = 12$ m provides a great reduction in the vibration level at 40–80 Hz.

4 Conclusions

Open and covered trenches are compared with regard to their efficiency as wave barrier. The trenches are lined by sheet-pile walls and backfilled with air-cushions and the analysis is carried out by a coupled boundary-element/finite-element scheme. It is found that the traffic-induced ground vibrations from a railway track or a road are reduced significantly by the barrier and that the connection between the two sheet-pile walls established by casting a concrete pavement on top of the trench has no significant impact on the efficiency of the barrier.

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