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MITIGATION OF TRAFFIC-INDUCED GROUND VIBRATION BY INCLINED WAVE BARRIERS— A THREE-DIMENSIONAL NUMERICAL ANALYSIS

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Double sheet pile walls can be used as wave barriers in order to mitigate ground vibrations from railways. The present analysis concerns the efficiency of such barriers, especially with regard to the influence of the barrier inclination and the backfill between the walls. Thus, the screening capabilities of an open trench, lined by sheet pile walls, are compared to those of a barrier with the original soil between the walls or a trench closed by a lid at the top. To this purpose, a three-dimensional boundary-element/finite-element model has been developed, based on a formulation in a moving frame of reference following the load. This allows a computation of the steady state response to a harmonically varying point source moving at different speeds typical for a train.

1. Introduction

Ground vibrations from roads and railways may be a nuisance to people and cause structural damage in built-up areas. In order to obstruct the wave propagation in the soil, wave barriers can be constructed along the track. Since the 1960s, research has been carried out regarding the efficiency of such barriers[1–6] with the general conclusion that the depth of the barrier is the major contributing factor. Furthermore, open trenches are generally better than backfilled barriers, since no waves are transmitted through the void. However, an open trench may not be a practical solution, since rain or percolating water will fill up the trench, reducing the impedance mismatch relatively to the ground significantly. Hence, instead of an open trench, a barrier backfilled with aircushions may be used[7].

A previous study, based on a two-dimensional numerical model, indicates that efficient wave barriers can be achieved by means of driven sheet piles[8–9]. In particular, a sandwich structure with two sheet pile walls flanking an open trench provides a great reduction in the vibration level outside the barrier. The inclination of the barrier has significant impact on the response measured along the surface of the ground[8], and the efficiency is only slightly reduced when the trench is closed at the top by, for example, a concrete pavement[9]. However, ground vibration from traffic is not induced by line loads, but by a number of point forces travelling along the track. Consequently, in this paper an analysis is carried out in the frequency domain, employing a three-dimensional model based on a coupled finite-element/boundary-element scheme formulated in a moving frame of reference following the travelling load. A parameter study is carried out, regarding the influence of the excitation frequency, the barrier inclination and the load speed. The quality of the barrier is evaluated based on its ability to mitigate vertical as well as horizontal vibrations along the ground surface.

2. Numerical model of railway track, ground and barrier

The analysis concerns a point source moving along a railway track resting on an embankment over homogenous soil. Sheet-pile walls are installed along the track to form a 1 m wide and 6 m deep barrier, 8 m from the centre of the track and with different inclinations. Exploiting symmetry, only half the track and the subsoil are modelled, employing a coupled finite-element/boundary-element (FE/BE) scheme in the frequency domain, see Fig. 1. In order to obtain the steady-state response, the problem is formulated in a moving frame of reference following the load[5,10–11].

Table 1. Material properties for isotropic materials.

	Young's modulus E [MPa]	Poisson's ratio ν [-]	Mass density ρ [kg/m^3]	Loss factor η [-]
Soil (half-space)	100	0.47	2000	0.03
Soil (embankment)	200	0.25	2000	0.05
Steel (rails)	21,000	0.30	7850	0.01
Concrete (lid)	2,500	0.15	2500	0.02

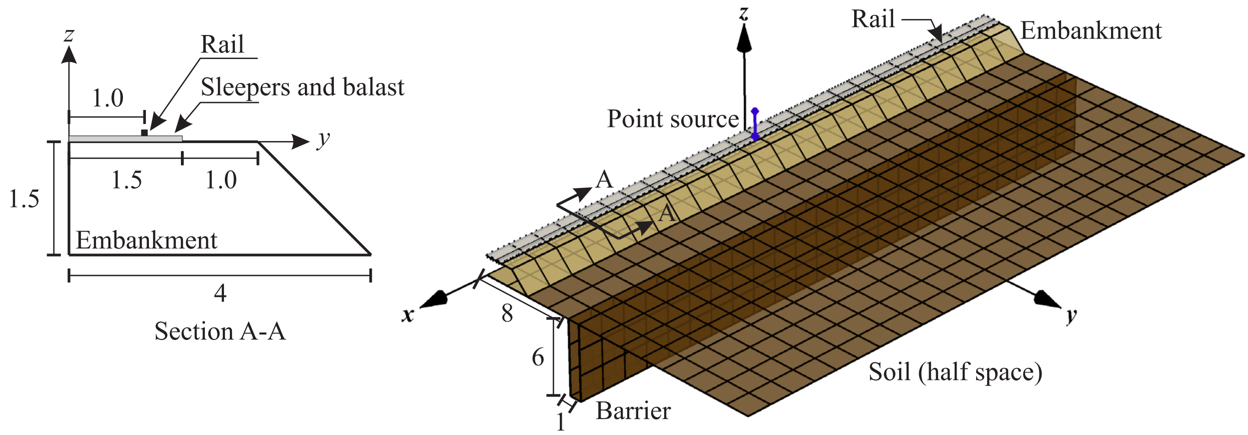

Figure 1. Geometry of the coupled BE/FE model for a fixed point source. Lengths are in metres.

The distance between the rails is 2 m, each rail being modelled as a Bernoulli-Euler beam with the cross-sectional area 0.02 m^2 and the bending moments of inertia $1\cdot10^{-4}$ m^4 and $2\cdot10^{-5}$ m^4 around the y-axis and the z-axis, respectively (see Fig. 1). The torsion constant is $1.2\cdot10^{-4}$ m^4 and the material properties listed in Table 1 are used, employing a convective FE scheme[5]. The sleepers and the ballast are modelled as a continuous, 0.2 m thick orthotropic slap with the Young's moduli E_1 = 200 MPa and E_2 = 50 GPa, where directions 1 and 2 coincide with the x- and y-directions, respectively. Poisson's ratio is ν_{12} = 0.001 and the shear moduli are $G_{12} = G_{13} = 0$ and G_{23} = 20 MPa. The mass density is 2100 kg/m^3 and the loss factor is 0.05, assuming a hysteretic material damping model. The properties have been calibrated to represent concrete sleepers ballasted with quarry rock. Each sleeper is 3 m wide, 200 mm high and 200 mm long, and the interspace between sleepers is 0.8 m. Quadrilateral Mindlin-Reissner plate elements with nine nodes and quadratic interpolation of the displacements and rotations are applied, using selective integration to avoid shear locking.

The embankment is 1.5 m high, 5 m wide at the top and 8 m wide at the base. The material properties for the embankment and the subsoil are given in Table 1. This provides P- and S-wave speeds of approximately c_P = 550 m/s and c_S = 130 m/s in the subsoil, corresponding to residual soil (clay/sand) of medium stiffness. In the embankment, the speeds are $c_P \approx 350$ m/s and $c_S \approx 200$ m/s. The soil is modelled by open boundary element domains, ensuring a radiation of the waves away from the source. Quadrilateral elements with nine nodes and quadratic interpolation of the displacement and the surface traction are used. The Green's function for a moving load is utilised[10–11] and it has been found that 16 × 16 Gauss points per element provides a solution of high accuracy. Each boundary-element domain is converted into a macro finite element to allow a coupling with the FE parts of the model[5,8,10]. The sheet pile walls are modelled as 0.5 m thick Mindlin-Reissner plates with $E_1 = 5$ MPa, $E_2 = 5$ GPa, $\nu_{12} = 0$, $G_{12} = G_{13} = G_{23} = 200$ MPa, $\rho = 150$ kg/m^3 and $\eta = 0.02$. Here, direction 1 coincides with the x-direction and direction 2 is co-directional with the sheet piles. The properties resemble steel sheet piles with the plate thickness 10 mm and the profile height 400 mm. The space between the walls is either taken up by the original soil or backfilled with aircushions[7]. In the latter case, the barrier is left open at the top, or a 200 mm thick concrete lid with the properties listed in Table 1 is included. Again, Mindlin-Reissner plate elements are used.

The coupled FE/BE analyses are carried out for sources moving at three speeds: $v = 0$ m/s (a fixed source), $v = 30$ m/s and $v = 60$ m/s, covering the typical range of train speeds in urban areas. The loads act on the rails in the z-direction (vertically) at $x = 0$ with the total magnitude 1 N and vary harmonically at the frequencies 10, 20 or 30 Hz. Due to the linearity of the model, the response to a moving train can be found by superposition. Three inclinations of the barrier are included in the parameter study, see Fig. 2. The V-shaped barrier goes 1 m in the negative y-direction per 2 m in the negative z-direction. Similarly, the A-shaped barrier goes 1 m in the positive y-direction per 2 m in the negative z-direction, whereas the H-barrier goes straight into the ground.

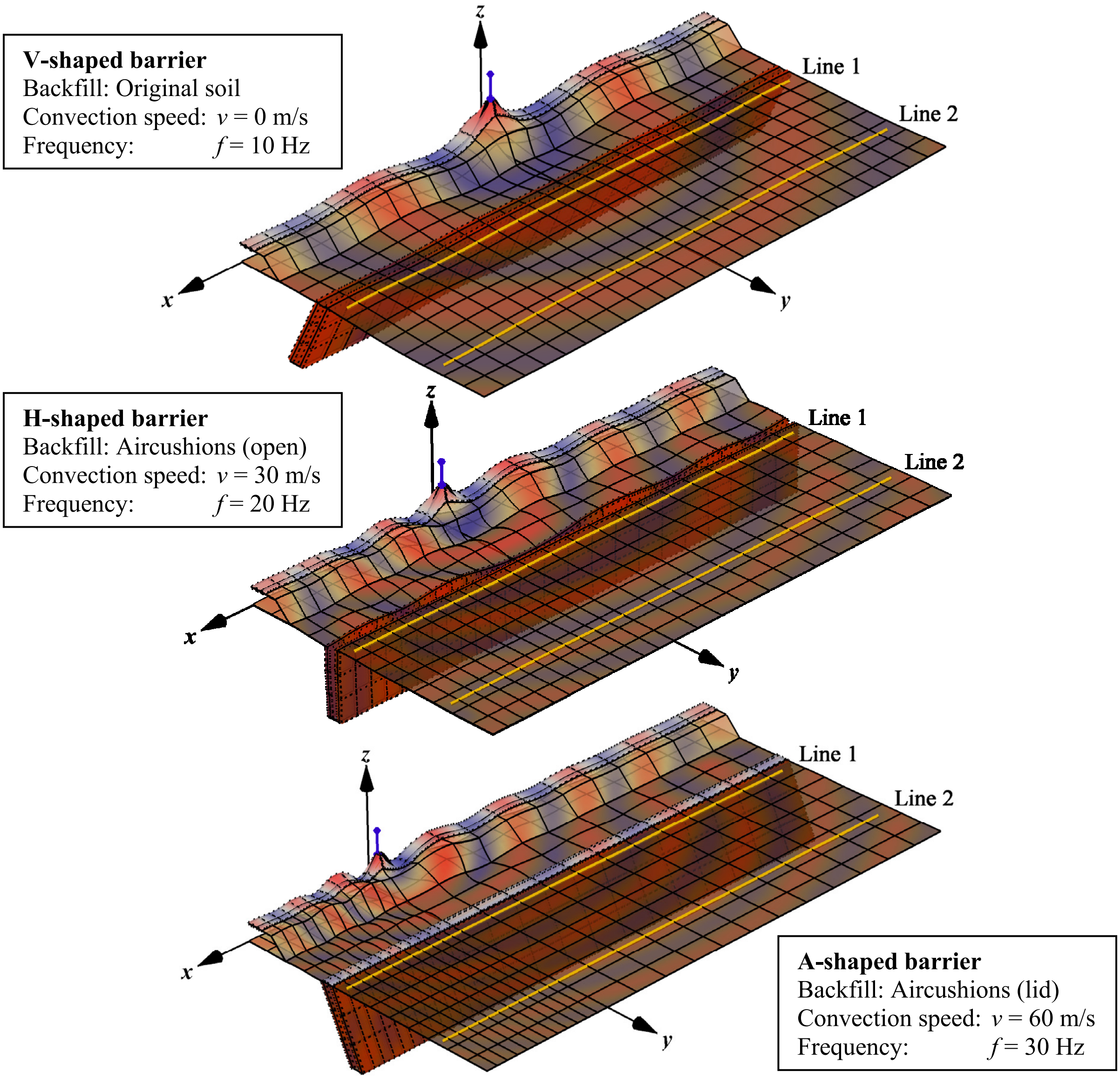

Figure 2. Example results of the coupled BE/FE analysis.

In Fig. 2, the red and blue shades indicate vertical displacements upwards and downwards, respectively, in phase with the point force. No artefacts occur in the results near the truncation of the computational grid, even though no transmitting boundary conditions[10,12] have been applied for the FE parts of the model. Thus, accurate results are achieved two element lengths from the edge of the computational model. The mesh size for $v = 0$ m/s is 2×2 m^2 in most parts of the model (see Figs. 1 and 2). Obviously, the elements are only 1 m wide (i.e. along the y-axis) at the base and top of the barrier, and slightly wider/narrower elements are utilised in the track and embankment. In the moving frame of reference, the convection leads to a decrease of the wavelengths ahead of the source, whereas longer waves are observed behind the source. In order to maintain a minimum of five nodes per Rayleigh wavelength at the frequency $f = 30$ Hz, the mesh size in the x-direction for $v = 30$ m/s is changed to 1.5 m in front of the source and 2.5 m behind the source. For $v = 60$ m/s the mesh size is 1 m/3 m in front of/behind the source, cf. Fig. 2.

3. Results and discussion

The vertical and horizontal vibration magnitudes, $|U_V| = |U_z|$ and $|U_H|$, based on the resultant of U_x and U_y, obtained for all combinations of the frequency, the velocity, the barrier shape and the backfill are presented in Figs. 3 to 5. The reference solution is obtained using the same FE/BE model, but with no barriers. The results marked "soil" refer to original soil between the sheet pile walls, whereas "open"/"lid" denote results for barriers backfilled with aircushions with/without a lid at the top. The results are plotted for two lines on the surface of the ground along the track. With reference to Fig. 2, Lines 1 and 2 are placed 10 and 20 m, respectively, from the centre of the track, i.e. Line 1 is 1 m outside the barrier and Line 2 is 11 m outside the barrier. For reference, it is noted that the vertical response at the source point is about $1.5 \cdot 10^{-9}$ m (at 30 Hz) to $3 \cdot 10^{-9}$ m (at 10 Hz), i.e. about one order of magnitude higher than the response outside the barrier. In all the analyses, the horizontal response is approximately half the magnitude of the vertical response.

As expected, the efficiency of the barrier increases with an increase of the frequency, and the open trench performs better than the trench with the lid and the barrier with soil between the walls. When the soil between the walls is not replaced, the barriers may even provide a higher response than the reference case without barriers. This is in particular observed for the V-shaped barrier at 30 Hz; but at the frequency 10 Hz and the velocity 0 m/s, only the V-shaped barrier with soil between the walls provides less response along Lines 1 and 2 than the reference solution.

At 20 and 30 Hz the A-shaped barrier performs better than the H- and V-shaped barriers when the original soil is present between the walls or the barrier is closed by a lid at the top, except for the horizontal response at Line 1, i.e. right outside the barrier. However, at 10 Hz the V-shaped barrier is slightly better, in particular along Line 2, 10 m from the track. When the barrier is open and the load is moving at the velocity 60 m/s, the H-shaped barrier is generally more efficient in reducing vertical vibrations than the two other barriers for all analysed frequencies. At the lower convection speeds, 0 and 30 m/s, the V-shaped barrier, open at the top, is generally preferable regarding the reduction of the vertical as well as the horizontal response—especially at 20 Hz.

Regarding the variation of the response along the track, it is observed that the magnitude of the displacements is symmetric around the fixed load at $x = 0$. When the speed of the moving load is increased, the local tips in the response move in the negative x-direction. The magnitude of the peaks in front of the load increases, whereas peaks behind the load become less pronounced with an increase in velocity, especially regarding the reference solution along Line 1 at the frequencies 10 and 20 Hz. However, at higher frequencies and velocities, the effect is less significant due to the complex interference patterns of waves emanating from the embankment and transmitted through and diffracted under the barriers. In any case, the distance along the x-axis between two peaks in the response from a single point source should be compared to the distance between two axels or bogies on a train. For example, the V-shaped barrier with original soil is unfavourable at $f = 20$ Hz and $v = 30$ m/s if the bogie distance is about 25 m.

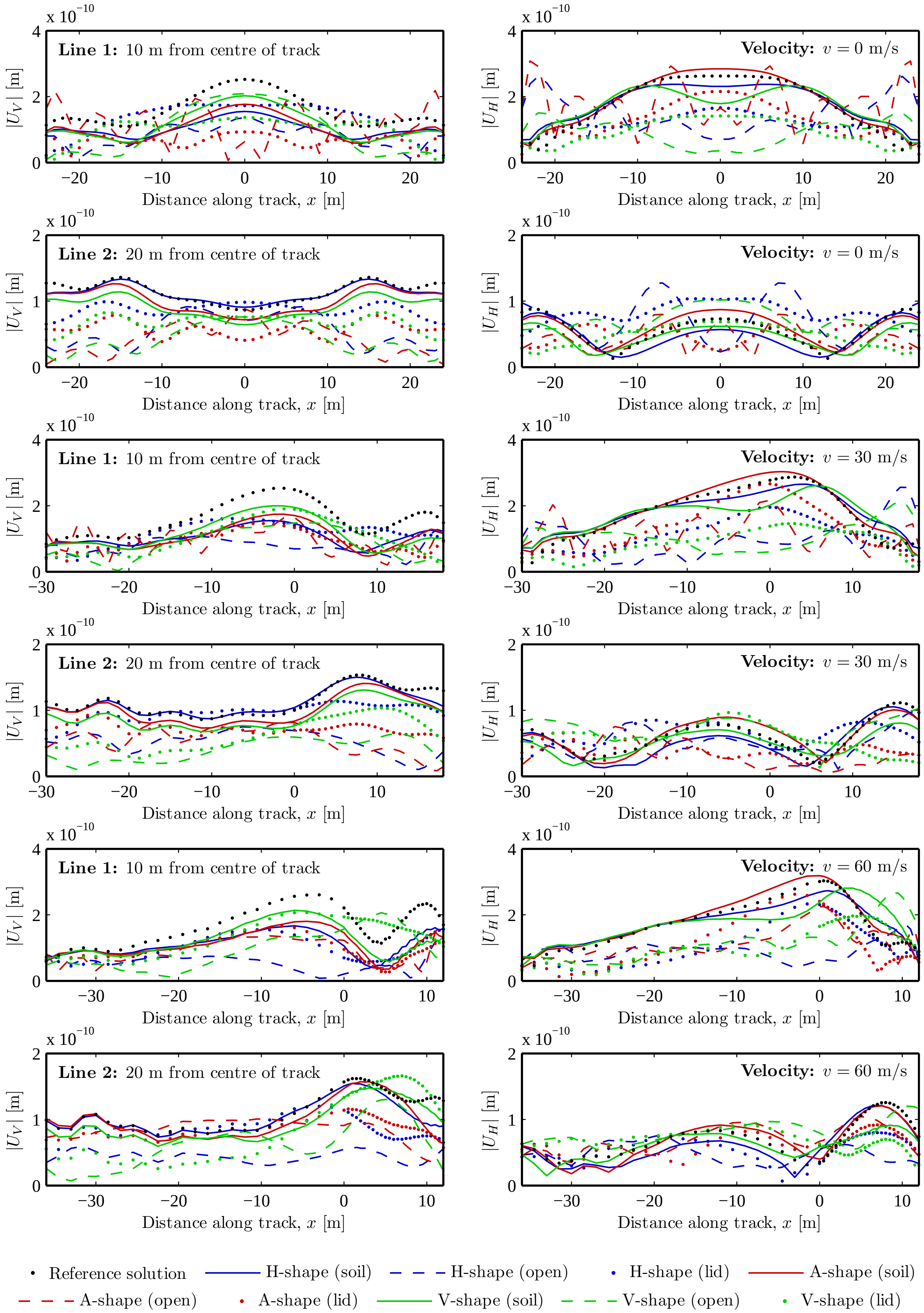

Figure 3. Response to a unit magnitude load obtained along Lines 1 and 2 at the frequency f = 10 Hz.

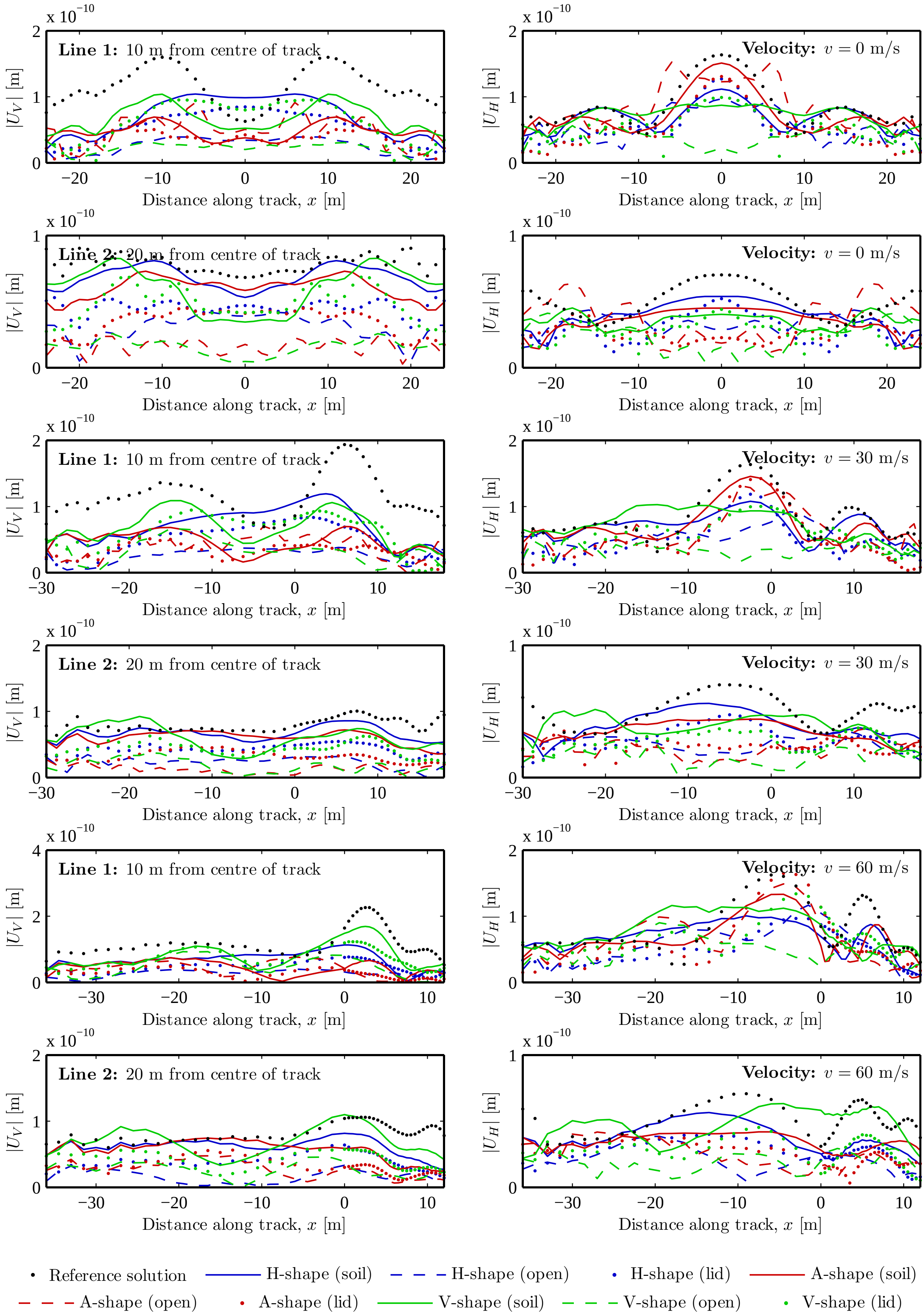

Figure 4. Response to a unit magnitude load obtained along Lines 1 and 2 at the frequency $f = 20$ Hz.

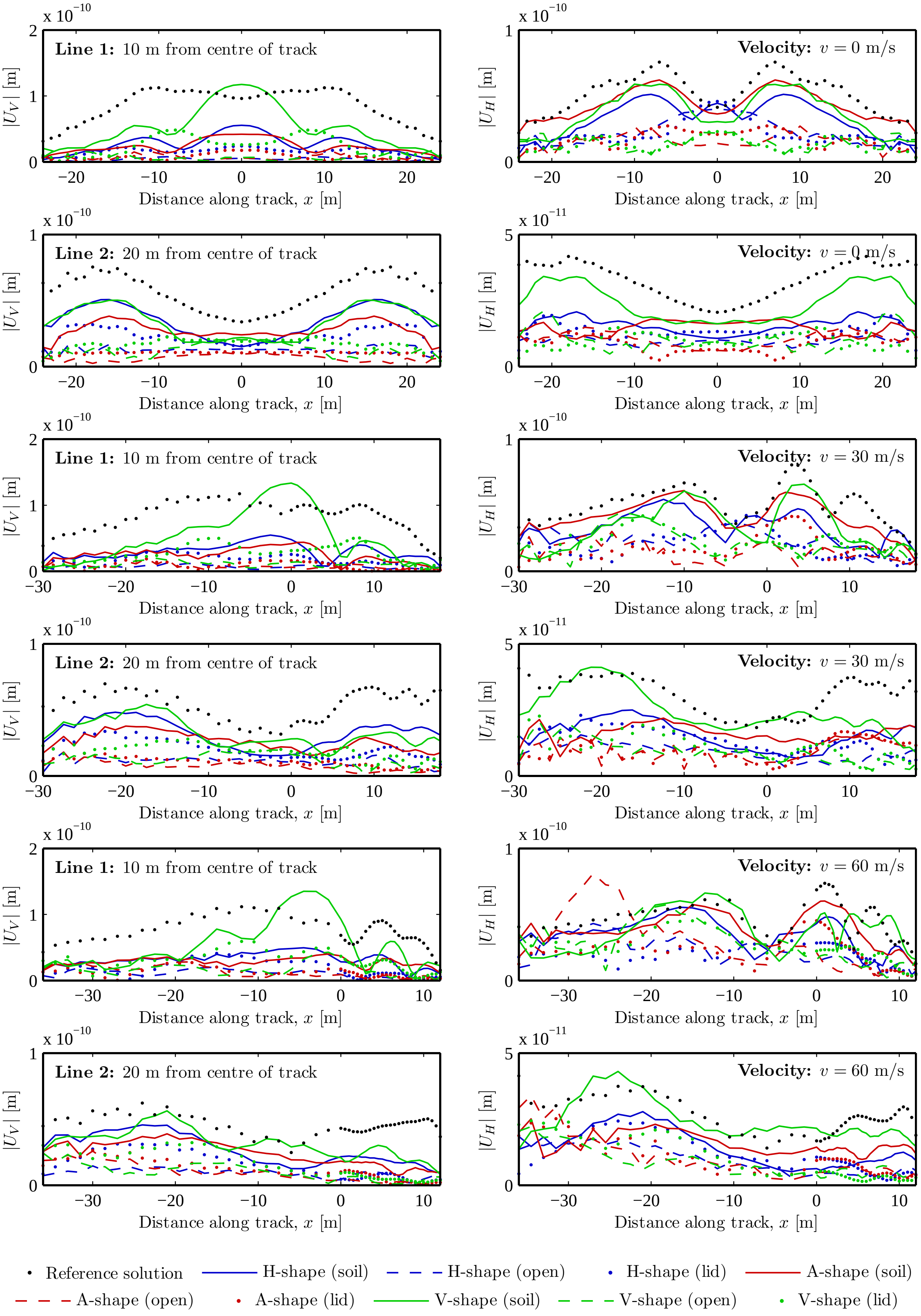

Figure 5. Response to a unit magnitude load obtained along Lines 1 and 2 at the frequency $f = 30$ Hz.

4. Conclusions

Open and closed trenches are compared with regard to their efficiency as wave barriers along a railway track. The trenches are lined by sheet pile walls and backfilled with original soil or air-cushions. In the latter case the effects of placing a lid at the top of the barrier has been investigated. The analyses are carried out in the frequency domain, representing the load by a point source varying harmonically at 10 Hz, 20 Hz and 30 Hz and moving with the speeds 0 m/s, 30 m/s and 60 m/s. Three inclinations of the wave barrier have been investigated, namely the H-shape, the V-shape, and the A-shape. The efficiency of the barriers all increase with increasing frequency, and the open trenches perform better than the trenches with a lid and the barriers with soil between the walls. The vibrations in the soil behind the barrier vary along lines parallel to the track, forming local tips and dips. A wave barrier along a track should be designed such that the distance between the tips and dips does not coincide with the distance between axels or bogies of a train. Finally, no unambiguous conclusions can be drawn regarding the efficiency of the barriers with respect to their inclination. At high velocities, the open H-shaped barrier provides the better screening. However, in practice an open barrier may be inconvenient and a lid at the top is required. Here, a slightly better result is achieved with the A-shaped barrier, compared to the V- and H-shaped barriers with a lid.

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