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Mitigation of railway induced vibrations by using subgrade stiffening and wave impeding blocks

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ABSTRACT: On sites with soft ground, stiffening of the subgrade beneath railway track has been associated with a reduction in ground-borne vibration. However, the mechanisms behind this reduction are not well understood. Here, the effects are examined in the context of two alternative approaches: (i) subgrade stiffening, where the soil directly under the track is stiffened, and (ii) wave impeding blocks, where stiff inclusions are positioned at some depth under the track. The efficacy of the measures are considered for three different ground types in a parametric study carried out using a 2.5D coupled finite-element / boundary-element methodology. With a 6 m wide, 0.5 m high concrete block directly under the track, the vibration between 8 and 50 Hz was reduced at the two sites with soft soil by between 2 and 8 dB at distances up to 32 m. In contrast, at the stiffer soil site, the reductions in vibration from this block were more modest (< 3dB). Similar reductions were observed for the three sites when the block was positioned 0.9 m below the surface (i.e. as a wave impeding block), suggesting that, as with stiffening directly under the track, the reduction in vibration was primarily due to the increase of the effective stiffness of the soil beneath the track rather than the effective creation of a new soil layer and resultant cut-on frequency. Jet grouting, whereby the ground is improved by cutting it with a high pressure water jet and then replaced with a cement grout, was considered as an alternative to concrete. Although it proved to be less effective due to the comparatively low stiffness, it may still be considered as a practical measure for existing track on soft soil sites.

KEY WORDS: Ground transmitted vibration, subgrade stiffening, wave impeding blocks, 2.5D modelling

1 INTRODUCTION

Ground-borne vibration is a commonly reported problem for residents of buildings near railway lines. Vibration is generated at the wheel/rail interface due to various mechanisms, including track unevenness or roughness, the quasi-static moving load effect, and the transient effects due to rail joints, switches and crossings [1]. Typically, ground-borne vibration is perceived as feelable whole-body vibration in the frequency range 1-80 Hz and as ground-borne noise in the frequency range 20-250 Hz. Vibration at higher frequencies is generally attenuated rapidly with distance along the transmission path through the ground [2]. In addition to annoyance of occupants, vibration can cause malfunction of sensitive equipment [3].

Ground-borne vibration can be attenuated by introducing isolation measures at the source, i.e. the track or vehicle, or at the receiver, i.e. a building, or by interrupting the transmission path. Vibration can be attenuated at the source [4,5,6] for example by using low-stiffness train suspensions, continuous rail support, soft railpads, resiliently mounted sleepers, under ballast mats or floating slab-tracks. Source attenuation can also include enhancing the track foundation and widening of the embankment. Vibration can be attenuated at a building [7] by placing resilient elements between the building and its foundation. A reduction of vibration can also be achieved for a particular part of the building, e.g. by isolating a floor or a whole room [8]. Attenuation in the transmission path can be achieved by interrupting the vibration transmission path [9-11], for example by using open trenches, in-filled trenches and rows of piles.

The work in this paper explores the effects of subgrade stiffening and wave impeding blocks on ground-borne vibration from surface railways. Stiffening of the subgrade beneath the railway track is often applied in soft soil sites to reduce track settlement and track deflections but has also been associated with a reduction in ground borne vibration [12–15]. Of note is that the method offers the prospect of vibration reduction at very low frequencies, in contrast to barrier methods which are effective only above a particular frequency as wavelengths and surface wave penetration depths get shorter. Various techniques can be applied to achieve the desired subgrade stiffening, e.g. vibro-compaction, vibro-replacement and jet grouting. In general these work either by compaction of the existing soil or by replacing some or all of the existing soil with a stiffer material. However, few practical tests have been reported, but where experimental results exist they look promising.

At the unusually soft soil site of Ledsgård in Sweden, the train speed exceeded the Rayleigh wave speeds of the upper soil layer resulting high levels of vibration below 10 Hz. Lime cement columns beneath the track were successfully used to alleviate the situation [16]. However it should be noted, there are no buildings in the vicinity of the track because of the unsuitable soil conditions and the main concern was to stabilize the track rather than reduce vibration. At similar sites in Kungsbaka in Sweden and at Rainham in England, concrete bridge decks supported on piles going through a soft layer into the lower stiffer material have been used to prevent excessive motion of the track.

A variant of subgrade stiffening is to stiffen the soil at some depth under the track rather than directly under the track. In the literature this has been referred to as a wave impeding block (WIB). It is thought that a mechanism of vibration mitigation in this case is that the stiffened block behaves like a rigid layer [17], in which case, wave propagation would only occur in the (softer) soil layer above it for frequencies higher than the cut-on frequency of this constrained layer. As such, the block should ideally be infinitely wide and stiff. The effect of a more 'practical' 12 m wide block 0.6 m deep concrete block positioned at a depth of 1.4 m was considered in [17] using a 2.5 FE/BE approach. The upper layer in this analysis was 2 m deep and very soft. Below this was a much stiffer half space. The results of the study were promising; the WIB provided more than 10 dB vibration reduction for all 1/3-octave frequency bands between 10 and 50 Hz.

Promising results have been found from computational analysis of subgrade stiffening, either directly below the track or at a depth. However, the number of cases considered so far has been limited and therefore it is not clear what the influence of parameters relating to the stiffened subgrade (e.g. geometry and material properties) and the soil (e.g. layering, material properties) influence the performance of the measures. This work, carried out as part of the EU funded RIVAS project, aims to investigate these factors.

2 METHODOLOGY

Within the RIVAS project, a parametric study has been conducted by project partners KU Leuven and ISVR to investigate the effectiveness of stiffening the soil under railway track as part of a wider study of mitigation measures in the transmission path. Initially, independent benchmark cases were considered by both partners. Subsequently, the remaining cases in the study were conducted by ISVR. In order to illustrate the principles, the study has been conducted in the context of three reference sites with differing soil conditions. Note that in none of these cases does the train run at speeds close to the Rayleigh wave speed, so the effect studied is the reduction of environmental ground vibration, not the mitigation of Rayleigh wave effects.

The stiffening blocks are filled with either concrete or with a material representative of jet grouting - the material parameters (density ρ, shear wave velocity C_s, Poisson's ratio ν, and material damping ratio β) are summarized in Table 5.

Table 1. Properties used for subgrade stiffening and wave impeding blocks

Layer	ρ [kg/m³]	C_s [m/s]	ν [-]	β [-]
Concrete	2400	1400	0.25	0.05
Jet grouting	2000	550	0.25	0.05

The parametric study is focused on three reference sites: Horstwalde, Lincent and Furet. The dynamic soil characteristics (layer thickness h, shear wave velocity C_s, compressional wave velocity C_p, density ρ, and material damping ratios β) for the three sites are given in Tables 2 to 4. The site at Horstwalde is a homogeneous half-space. The site of Lincent consists of two softer top layers with a total thickness of 4.1 m above a relatively stiff half-space. At the site of Furet, an inverse layering is present and the second, softest layer goes down to a depth of 12 m.

Table 2. Soil characteristics for the Horstwalde site.

Layer	h [m]	C_s [m/s]	C_p [m/s]	β [-]	ρ [kg/m³]
1	∞	250	1470	0.025	1945

Table 3. Soil characteristics for the Lincent site.

Layer	h [m]	C_s [m/s]	C_p [m/s]	β [-]	ρ [kg/m³]
1	1.4	128	286	0.044	1800
2	2.7	176	286	0.038	1800
3	∞	355	1667	0.037	1800

Table 4. Soil characteristics for the Furet site.

Layer	h [m]	C_s [m/s]	C_p [m/s]	β [-]	ρ [kg/m³]
1	2	154	375	0.025	1800
2	10	119	290	0.025	1850
3	∞	200	490	0.025	1710

The reference track used in the parametric study consists of UIC60 rails, supported by rail pads on monoblock concrete sleepers and a ballast layer with a thickness of 0.30 m. No sub-ballast, form layer or embankment is included. The parameters of the track are summarized in Table 5. The rails are modelled as Euler-Bernoulli beams, the rail pads and the sleepers using solid elements. The ballast is modelled as an elastic continuum.

Table 5. Characteristics of the track

Part	Characteristic	Value	Dimension
Rail	Bending stiffness	6.4	[x10^6 Nm²]
	Mass per unit length	60	[kg/m]
	Gauge	1.435	[m]
Rail pad	Stiffness	300	[x10^6 N/m]
	Loss factor	0.10	[-]
Sleeper	Length	2.60	[m]
	Width	0.25	[m]
	Height	0.20	[m]
	Mass	325	[kg]
	Young's modulus	30	[x10^9 N/m²]
	Poisson's ratio	0.15	[-]
	Sleeper distance	0.60	[m]
Ballast	Thickness	0.30	[m]
	Shear wave velocity	300	[m/s]
	Poisson's ratio	1/3	[-]
	Density	2000	[kg/m³]
	Material damping ratio	0.02	[m]
	Upper width	3.6	[m]
	Lower width	5.6	[m]

The geometry of a railway line with the measures described here is two-dimensional but the loading due to a train introduces a dependence on the third (longitudinal) dimension. By assuming homogeneity of the geometry and material properties in the track direction, the response along this third dimension can be formulated in terms of the wavenumber and a Fourier transform used to recover the three-dimensional response. This '2.5D' method is computationally more efficient than a full 3D approach. In the models used here, the track is modelled using finite elements (FE) while the ground and stiffened soil are modelled using boundary elements (BE) (Figure 1). The ground and block elements have a maximum node-to-node distance of 0.25 m at the half-space site (Horstwalde), and 0.3 m at the layered sites (Lincent and Furet). This was sufficient to ensure that there are at least 6 nodes per wavelength up to 66 Hz for all three sites and 4 nodes per wavelength up to 99 Hz. To reduce the corner effects, smaller elements (node-to-node distance of 0.025 m) are used to mesh the ground within 0.2 m on each side of the corners. At Horstwalde, the mesh extends from 3.5 m on one side of the track to 68 m on the other, at Lincent and Furet, the mesh on the calculation side was restricted to 34 m due to model limitations.

Similar 2.5D coupled FE-BE approaches have been adopted by ISVR and KU Leuven. However, in the KU Leuven method the 2.5D FE model is combined with the 2.5D BE model using 2.5D Green's function of a horizontally layer half-space [18]. Additionally, the stiffened block is modelled using finite elements rather than boundary elements.

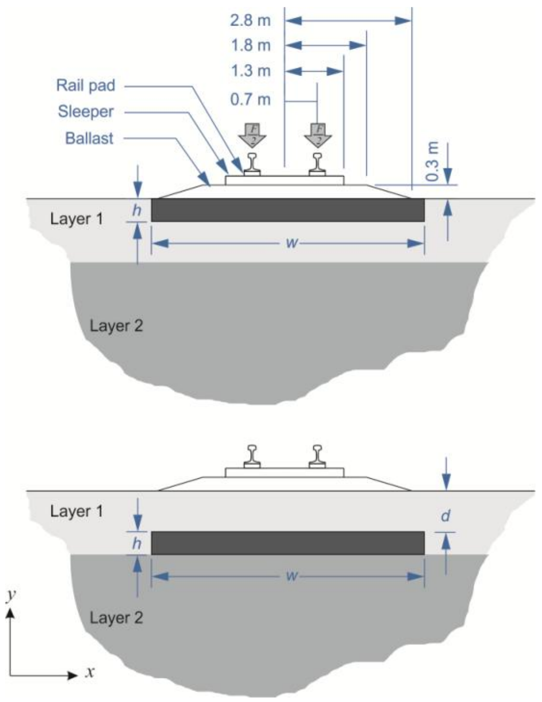

Figure 1. Example sketch of track section at layered soil site of Lincent with soil stiffening (top) and wave impeding block (bottom)

3 BENCHMARK REFERENCE CASES

Initially, reference cases with a block 6 m wide and 0.5 m thick were considered by ISVR and KU Leuven. The block was located either directly under the track for subgrade stiffening or at a depth of 0.9 m for a wave impeding block. As will be seen in Section 4.1 and 5.1 it is important to consider the track in the model and therefore it is included here. Figure 2a shows the transfer mobilities between point forces of amplitude 0.5 applied to each rail and the vertical displacement at a receiver position 16 m from the track with and without subgrade stiffening. The agreement between the two models is good below 30 Hz. Between 30 Hz and 75 Hz the mobility predicted by the ISVR model is higher, while at higher frequencies it is lower. The reason for the differences above about 50 Hz is associated with differences in the sleeper models used. In the KU Leuven model the sleepers are modelled as distributed masses which are rigid in the plane of the cross-section, whereas in the ISVR model the sleepers are represented by smeared properties in the longitudinal direction including bending stiffness. The corresponding insertion losses are given in Figure 2b. Good agreement can be seen up to around 75 Hz. The benefits on this relatively stiff-soil site are modest (< 4 dB) and are restricted to frequencies above around 20 Hz.

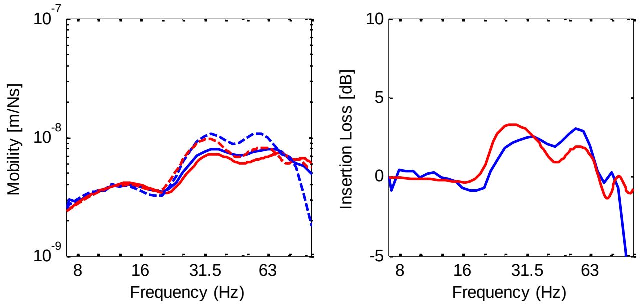

Figure 2 Transfer mobility (2a) and insertion loss (2b) for a point load at a distance of 16 m for subgrade stiffening (6 m wide, 0.5 m high) at the Horstwalde site. Solid line: with subgrade stiffening, dashed line: without subgrade stiffening. ISVR (red), KU Leuven (blue).

The comparisons between partners for the wave impeding block can be seen in Figure 4. Again, differences between the mobilities at frequencies above around 50 Hz are associated with the difference in the track model. At low frequencies the insertion loss is negligible (or even negative) but from approximately 25 Hz, a reduction in vibration levels can be seen. The insertion loss rises to around 3−5 dB at higher frequencies.

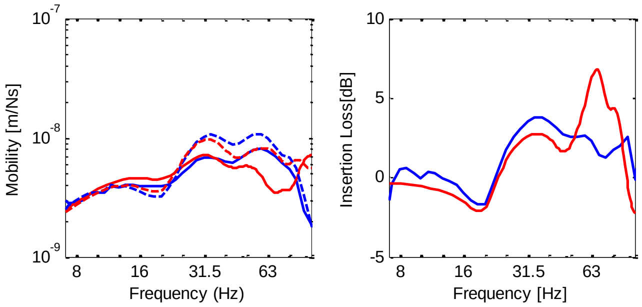

Figure 3 Transfer mobility (3a) and insertion loss (3b) for a point load at a distance of 16 m for a wave impeding block (6 m wide, 0.5 m thickness, 0.9 m deep) at the Horstwalde site. Solid line: with subgrade stiffening, dashed line: without subgrade stiffening. ISVR (red), KU Leuven (blue).

4 STUDY OF SUBGRADE STIFFENING

4.1 *Influence of track*

For mitigation measures positioned away from the track (e.g. trenches), the presence of the track in the model has a minimal influence on the insertion loss. With subgrade stiffening, the block is placed directly under the track. Therefore, whether or not the track is included in the model is expected to have a greater influence. Figure 4 compares the track receptance at the three reference sites with and without the subgrade stiffening. In this case, the subgrade stiffening block is made of concrete and has a thickness of 0.5 m and a width of 6 m. The block is positioned directly under the ballast. In each case, the track receptance is lower at most frequencies when the subgrade stiffening block is included. This difference is greatest at the soft soil sites of Lincent and Furet where the increase in stiffness from the inclusion of the concrete block is greatest.

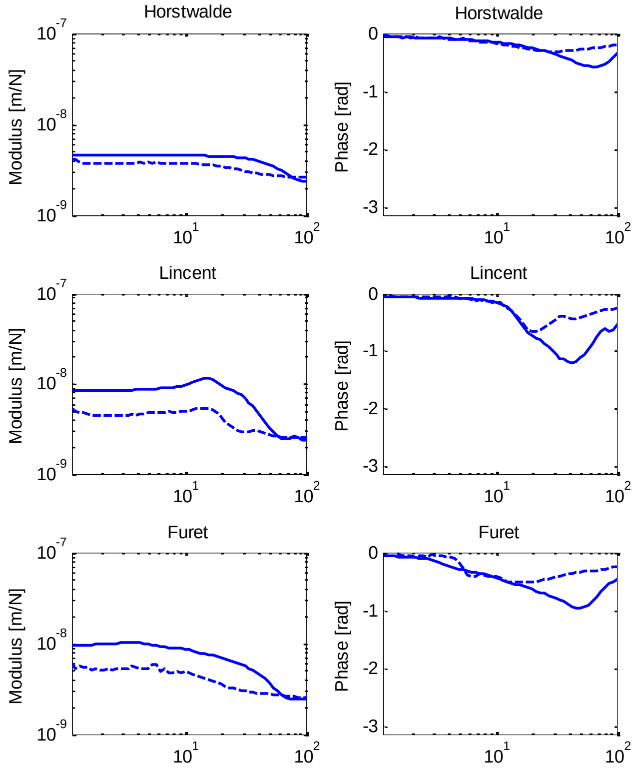

Figure 4. Track receptance with and without subgrade stiffening at the three reference sites. Solid line: without subgrade stiffening, dashed line: with subgrade stiffening.

Figure 5 shows the insertion loss at Horstwalde at various positions away from the track, based on calculations with and without the track. These results are for a point load. Without the track, the point load is at the centre of the track location (x=0). With track, it consists of a point load of amplitude 0.5 at each rail.

The stiffened block provides benefit from around 40 Hz at all distances. When the track is excluded from the model this benefit continues to increase with frequency but, with the track included, the benefit peaks at around 50 Hz and then drops off rapidly at frequencies above this. At 80 Hz the influence of the track can be as large as -10 dB. Due to this strong effect, for the remaining cases, the track is included in the model. In addition, a correction to account for the interaction between the track and the wheel is also applied in subsequent results. The changes in track receptance due to the subgrade stiffening affect the interaction force, which for a single wheel/rail contact is given by [1]:

$$F = \frac{r}{\alpha_r + \alpha_w + \alpha_c} \qquad (1)$$

where r is the roughness amplitude, α_r is the track receptance, α_w is the wheel (or vehicle) receptance, and α_c is the receptance of the contact spring. For the wheel receptance, a 3 degree-of-freedom model is used including the primary and secondary suspensions. At low frequency the wheel receptance is much greater than the track receptance and the contact force is unaffected by the change in track receptance. However, above 50 Hz the wheel and track receptances have similar magnitudes and the change in contact force must be taken into account. Examples of the correction are shown in Figure 6. As seen from the figure, the change in contact force is larger at high frequencies.

In subsequent calculations a 'line load' is considered. This consists of a series in incoherent point loads at the locations of the axles of a typical four car EMU train of length 106 m.

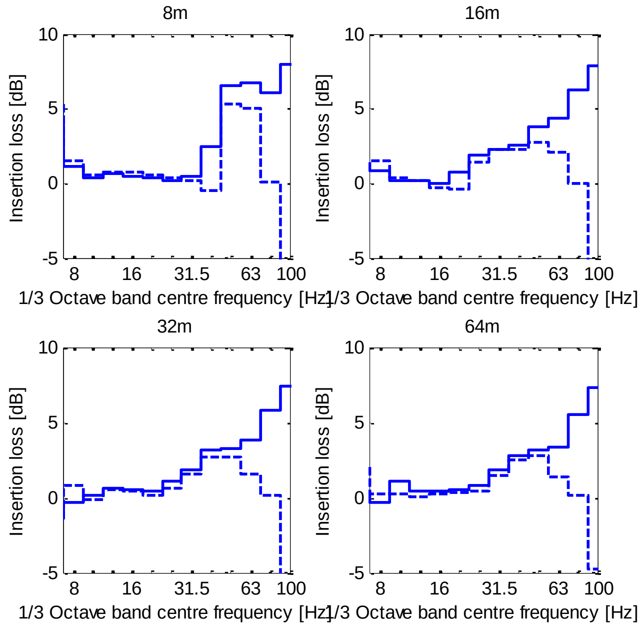

Figure 5. Insertion loss for subgrade stiffening, at Horstwalde without (solid line) and with (dashed line) track.

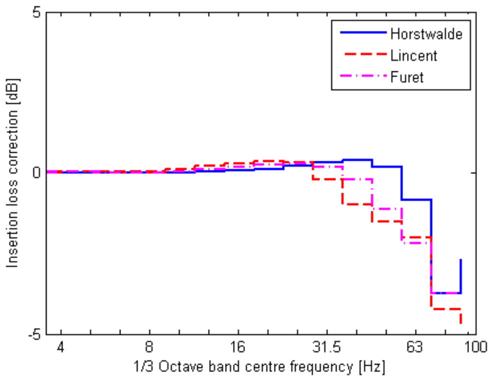

Figure 6. Insertion loss correction due to vehicle/track interaction for subgrade stiffening at the reference sites.

4.2 Influence of soil conditions

The insertion loss of the same 0.5 m thick and 6 m wide concrete block as used in Section 4.1 is plotted in Figure 7 for all three reference sites. The purpose of introducing subgrade stiffening is to reduce ground-borne vibration due to the increase of the effective stiffness of the soil beneath the track. It was expected that the vibration would be reduced in the lower frequency range, for all distances from the track and particularly at sites with an initially soft soil. The results confirm this, as can be seen in Figure 7, with the block having a limited influence for Horstwalde where the soil is relatively stiff, whereas for the softer layered sites of Lincent and Furet benefits of around 5 dB are obtained.

At high frequencies, however, the insertion loss is negative. This is caused by an increase in track receptance, see Figure 4, and corresponding increase in transfer mobility, possibly due to a resonance of the block mass on the ground stiffness. In addition the interaction force is increased, as shown in Figure 6, leading to a further reduction in insertion loss at high frequencies.

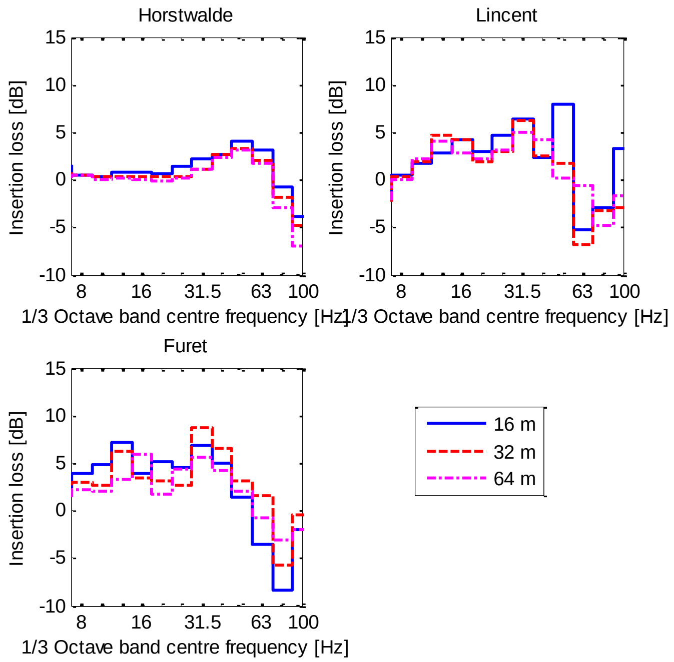

Figure 7. Effect of soil conditions on the insertion loss resulting from subgrade stiffening. Responses at 16 m (blue solid line), 24 m (red dashed line) and 32 m (purple dash-dot line) to a line source. Corrected for vehicle/track interaction.

4.3 Influence of material

The influence of the material of the subgrade stiffening block has been investigated. Since a solid concrete block would be difficult to install once a track has been constructed, jet grouting is considered as an alternative. Jet grouting is a process of improving the ground by cutting it with a high pressure jet and mixing, and replacing the resulting slurry with cement grout. As a result the soil under the track can be much stiffer than the normal soil but less stiff than concrete.

The effect of changing the material to represent jet grouting is calculated only for Lincent. The results are shown in Figure 8, indicating that jet grouting is much less effective than concrete. At higher frequencies (>60Hz), the jet grouted block performs somewhat better, although it should be noted that with both blocks the insertion loss is negative at these frequencies indicating that the block increases the vibration.

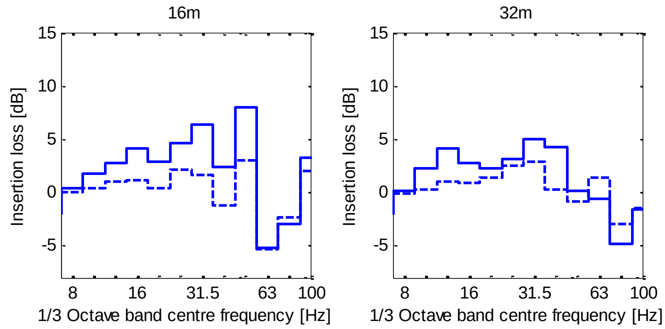

Figure 8. Insertion loss at Lincent, concrete (solid line) and jet grouting (dashed line). Response to a line source. Corrected for vehicle/track interaction.

4.4 Influence of thickness of subgrade stiffening block

Increasing the thickness of the subgrade stiffening block further increases the stiffness of the track foundation, reducing the track receptance. In Figure 9 and Figure 10 the thickness of the block is varied between 0.5 and 2.0 m, for both Lincent and Furet sites. The width of the block is kept at 6 m. As expected, increasing the thickness of the block improves the insertion loss. This improvement occurs at most frequencies and is greatest at the very soft soil site of Furet. The benefits of subgrade stiffening at very low frequencies at soft soil sites are noteworthy, as subgrade stiffening is one of the few measures that has the potential to reduce vibration at very low frequencies.

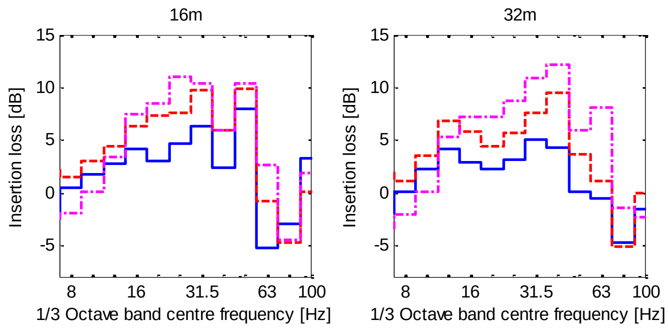

Figure 9. Effect of block thickness on the insertion loss of subgrade stiffening for Lincent: 0.5 m thick (blue solid line), 1 m thick (red dashed line) and 2 m (purple dash-dot line).

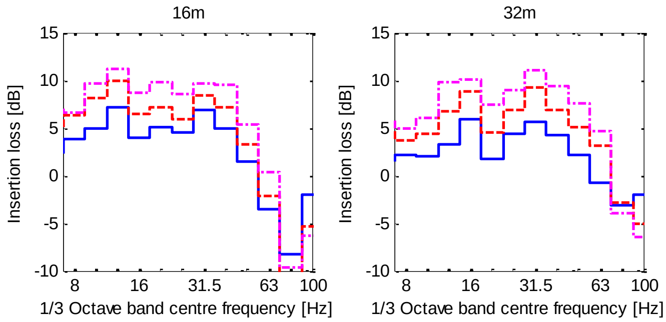

Figure 10. Effect of block thickness on the insertion loss of subgrade stiffening for Furet: 0.5 m thick (blue solid line), 1 m thick (red dashed line) and 2 m (purple dash-dot line).

5 STUDY OF WAVE IMPEDING BLOCKS

5.1 Influence of track

In this section a wave impeding block, such as shown in Figure 1b, is considered. As with subgrade stiffening, the influence of the track is first investigated for the half-space site of Horstwalde. The wave impeding block is constructed from concrete and is 0.5 m in thickness, 6 m in width. The top surface is 0.9 m below the surface of the ground.

Insertion losses at various distances are shown in Figure 11, calculated with and without the track. The track influences the results at most frequencies and receiver positions to some degree, the influence can be as large as 5 dB. Consequently, the track is included in the model for all subsequent wave impeding block cases.

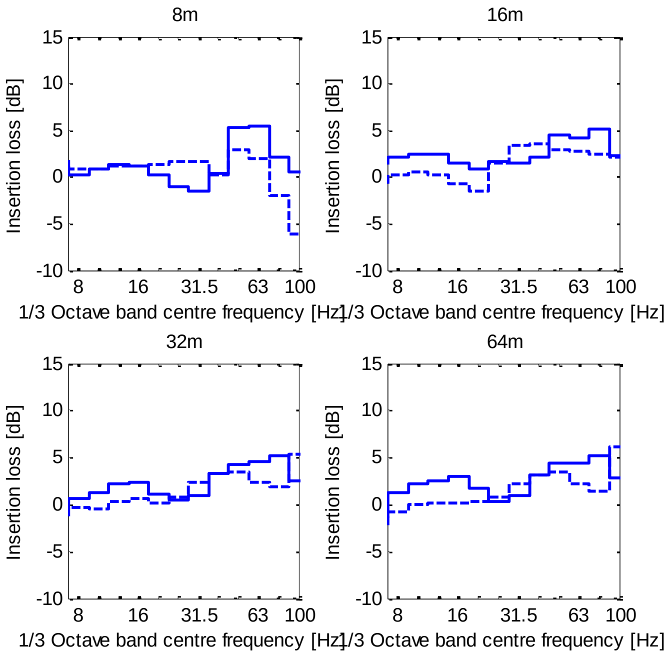

Figure 11. Insertion loss for wave impeding block at Horstwalde without (solid line) and with (dashed line) considering track. Response to point load (uncorrected).

The correction described in Section 3 to account for the change in wheel/rail interaction force is also applied here. The results are shown in Figure 12. It can be seen that the correction is significant for frequencies of 31.5 Hz and above, with a maximum of around 3 dB. It has more effect on lower frequencies than for the case of subgrade stiffening (Figure 6).

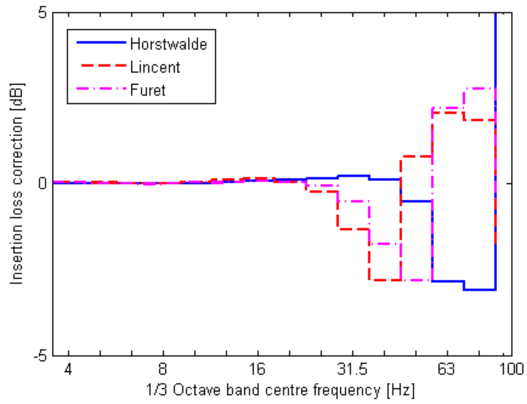

Figure 12. Insertion loss correction due to vehicle/track interaction for wave impeding blocks at the reference sites.

5.2 Influence of soil conditions

Results for the same wave impeding block (0.5 x 6 m, depth 0.9 m) are shown for all three sites in Figure 13 for various receiver positions. Similarly to stiffening directly under the track, the performance depends on the soil conditions with the low frequency benefits most apparent at the soft soil sites of Lincent and Furet. At Furet there is a benefit of at least 5 dB in all third-octave bands up to 31.5 Hz. At higher frequencies the presence of the stiffened block results in a negative insertion loss, particularly for the Lincent site.

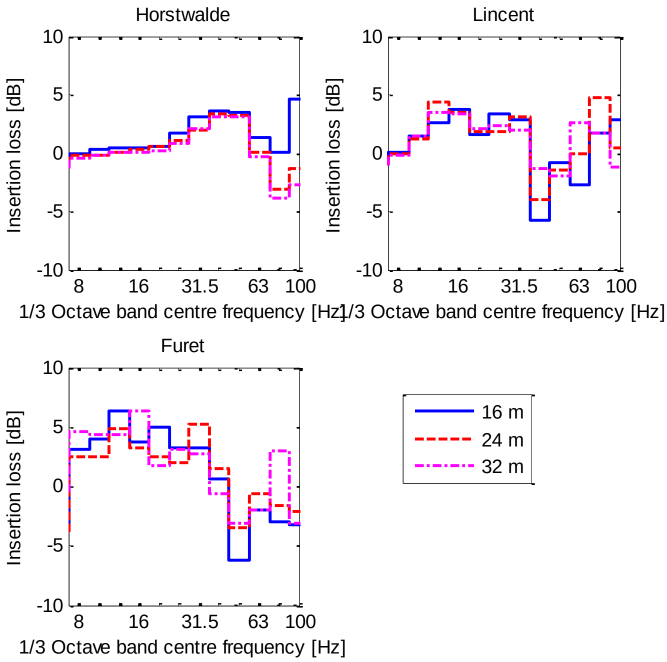

Figure 13. Effect of soil conditions on the insertion loss resulting from a wave impeding block. Responses at 16 m (blue solid line), 24 m (red dashed line) and 32 m (purple dash-dot line).

5.3 Influence of material

As for subgrade stiffening, two different materials, concrete and jet grouting, are investigated as potential materials for the wave impeding block. Jet grouting may be considered a more viable alternative for existing track. Results for Lincent are shown in Figure 14. As expected, the jet grouting material is generally less effective, with the benefit being around half that of concrete.

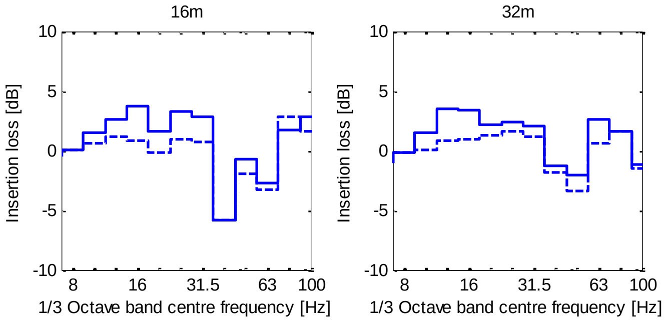

Figure 14. Insertion losses at Lincent, wave impeding blocks, using concrete (solid line) and jet grouting material (dashed line). Response to a line source. Corrected for vehicle/track interaction

5.4 Influence of width of wave impeding block

The concept behind a wave impeding block was thought to be that a stiff layer is created at some depth, resulting in a cut-on frequency of the soft upper soil layer above it. As such, the ideal block would be rigid and infinite in width. The effect of the width of the block is investigated for the Horstwalde site and the results are shown in Figure 15. With the infinitely wide block it can be see that a cut-on frequency is created, with the insertion loss rising steeply from around 25 Hz. There is a peak in the insertion loss at around 50 Hz. At frequencies above the cut-on frequency the insertion loss increases with distance from the track. At low frequencies the insertion loss is negative. In contrast, with the finite width block the benefits around this cut-on frequency are very much reduced, with less than 5 dB reduction even for a 12 m wide block. These benefits are relatively consistent with distance. This suggests that while there is potential for mitigation above a cut-on frequency through the creation of a stiff layer, for realizable blocks the benefits are mainly at low frequency where the blocks act to stiffen the subgrade in a similar manner to placing the blocks directly under the track.

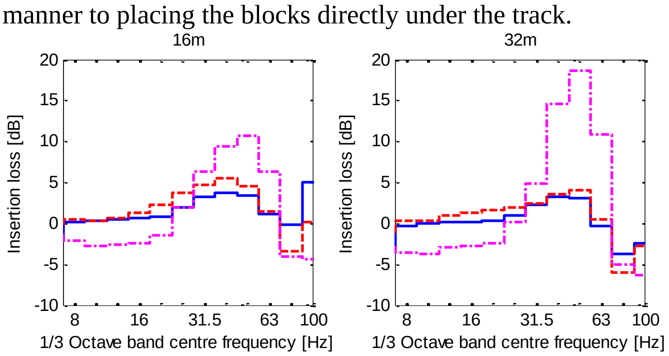

Figure 15 Insertion losses at Horstwalde, wave impeding blocks with widths of 6 m (blue solid line), 12 m (red dashed line) and infinite (purple dot-dash line). Response to a line source. Corrected for vehicle/track interaction.

5.5 Influence of thickness and depth of wave impeding block

Here the influence of the thickness and depth (from the ground surface) of the wave impeding blocks is investigated for the soil conditions at Lincent. Two combinations are considered: i) 0.5 m thick block, 0.9 m below the surface (as before); and ii) 1.0 m thick block, 0.4 m below the surface. Since the depth of first soft layer soil at Lincent is 1.4 m, in both cases the wave impeding block sits on the top of the second soil layer. It should be noted, however, that the second layer at this site, between 1.4 m and 4.1 m, is also relatively soft and therefore the impedance mismatch between the two layers is relatively small.

Results are shown in Figure 16. From the figure, the thicker block placed at a shallower location has a better performance for frequencies up to about 50 Hz. The improvement can be as large as 5 to 8 dB for some frequency bands. A similar effect is found when increasing the thickness of subgrade stiffening soil under the track (see Figure 9). As the thickness of subgrade stiffening affects the receptance and transfer mobility it seems likely that the thickness of the block rather than its location below the surface is the important parameter here.

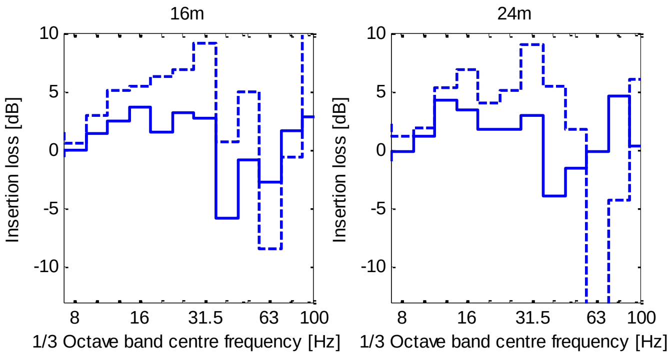

Figure 16. Insertion losses at Lincent, 6 m wide wave impeding blocks. Solid line: thickness of the block is 0.5 m, depth to the top of the block in the soil 0.9 m; Dashed line: thickness of the block is 1 m, depth to the top of the block in the soil 0.4 m. Response to a line source. Corrected for vehicle/track interaction

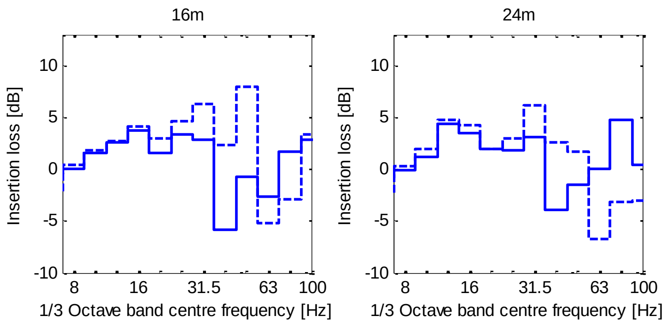

Figure 17. Insertion losses at Lincent, concrete block with width of 6 m in width and thickness of 0.5 m. Solid line: wave impeding block, depth to the top of the block in the soil 0.9 m; Dashed line: subgrade stiffening, depth to the top of the block in the soil 0 m. Response to a line source. Corrected for vehicle/track interaction.

The results using the same size of concrete block as a subgrade stiffening block and a wave impeding block are compared in Figure 16 17. As seen from the figure, for the case studied here, there is only a slight difference due to moving the block from the surface (subgrade stiffening) to a deeper location (wave impeding block).

6 CONCLUSIONS

The effects of stiffening the soil, either directly under the track or at some depth have been considered using 2.5D FE/BE simulations. Initial benchmark cases showed reasonable agreement between independent calculations by two project partners. Subsequent to these a parametric study was carried out to investigate factors affecting the performance of the measures.

The concept behind introducing subgrade stiffening directly under the track is to reduce the ground-borne vibration due to the increase of the effective stiffness of the soil beneath the track. As expected, the track receptance was found to decrease when a 6 m wide, 0.5 m thick concrete block was inserted beneath the track. At the relatively stiff-soil site, the reductions in vibration from this block were modest (< 3dB) and restricted to frequencies greater than around 50 Hz. In contrast, at the soft soil sites the performance of the 6 m wide, 0.5 m thick block was more impressive (2-8 dB), providing benefit at frequencies between 8 and 50 Hz. Increasing the thickness of the block from 0.5 m to 2.0 m increased the performance by up to 5 dB, with reductions of around 7 dB expected even in the lowest frequency bands. At higher frequencies (63 Hz and above) the insertion loss of the blocks is negative indicating an increase in vibration; however these frequencies are likely to be less problematic at soft soil sites. The benefits of subgrade stiffening at Furet in particular are noteworthy, as this is one of the few measures that have potential to reduce vibration at very low frequencies at such soft soil sites.

Since a solid concrete block would be difficult to install once a track has been installed, jet grouting has been considered as an alternative to stiffen the soil under existing track. It was found to be less effective than concrete. Nevertheless, it could be a viable solution for existing track on soft soil sites, particularly if the soil is stiffened to a greater depth.

The motivation for considering a wave impeding block was that it was thought that it would affect wave propagation through the creation of a stiff layer at some distance beneath the surface. Accordingly, the ideal block would be rigid and infinite in width. An infinitely wide concrete block was modelled at Horstwalde. This resulted in a cut-on frequency being created at around 25 Hz, above which the vibration was attenuated. The peak reduction was around 18 dB at 50 Hz for a receiver position 32m from the track. When using a more practical 6 m wide, 0.5 m thick block, at a depth of 0.9 m below the surface there was some evidence of a cut-on frequency at all three reference sites. However, the benefits above this cut-on frequency were modest – reductions in vibration were mainly at low frequencies where the blocks acted to stiffen the subgrade in a similar manner to placing the blocks directly under the track. Indeed, compared with subgrade stiffening, similar results are obtained when using a wave impeding block with the same properties as the subgrade stiffening block.

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REFERENCES

[1] D.J. Thompson, Railway Noise and Vibration. Mechanisms, modelling and means of control, Elsevier, 2008.
[2] C.J.C. Jones and J.R. Block. Prediction of ground vibration from freight trains. Journal of Sound and Vibration, 193(1):205–213, 1996.
[3] H.E.M. Hunt and M.F.M. Hussein, Ground-borne vibration transmission from road and rail systems: prediction and control. Chapter 123, in, Crocker, Malcolm J. (ed.) Handbook of Noise and Vibration Control. New York, US, Wiley, 1458-1469, 2008.
[4] R. Hildebrand, Countermeasures against railway ground and track vibrations. Report at Department of Vehicle Engineering. Stockholm. 2001.
[5] P.J. Remington, L.G. Kurzweil and D.A. Towers, Low-frequency noise and vibration from trains. Chapter 16 in Transportation Noise Reference Book, ed. P.M. Nelson, Butterworth, 1987.
[6] G.P. Wilson, H.J. Saurenman and J.T. Nelson, Control of ground-borne noise and vibration. Journal of Sound and Vibration, 1983, 87(2), pp. 339-350.
[7] J.P. Talbot, Base isolation of buildings for control of ground-borne vibration. Chapter 124 in Crocker, Malcolm J. (ed.) Handbook of Noise and Vibration Control. New York, US, Wiley, 1470–1478, 2008.
[8] P. Fiala, G. Degrande, F. Augusztinovicz, Numerical modelling of ground-borne noise and vibration in buildings due to surface rail traffic, Journal of Sound and Vibration, 301(3–5), 2007, pp. 718-738.
[9] R.D. Woods, Screening of surface waves in soils. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American society of Civil Engineers, 1968, SM4, pp. 951-979.
[10] S.E. Kattis, D. Polyzos and D.E. Beskos, Modelling of pile wave barriers by effective trenches and their screening effectiveness. Soil Dynamics and Earthquake Engineering, 1999, 18, pp. 1-10.
[11] A. Alzawi and M. El Naggar, Full scale experimental study on vibration scattering using open and in-filled (GeoFoam) wave barriers, Soil Dynamics and Earthquake Engineering 31 (2011) 306–317.
[12] H. Takemiya and A. Fujiwara, Wave propagation/impediment in a stratum and wave impeding block (WIB) measured for SSI response reduction, Soil Dynamics and Earthquake Engineering 13, 49-61, 1994.
[13] G. Schmid, N. Chouw, and R. Le. Shielding of structures from soil vibrations. Proceedings of Soil Dynamics and Earthquake Engineering V, Computational Mechanics Publications, 1992. 651–662.
[14] A.T. Peplow, C.J.C. Jones, and M. Petyt. Surface vibration propagation over a layered elastic halfspace with an inclusion. Applied Acoustics, 56(4), 283–296, 1999.
[15] H. Takemiya, N. Chouw, and G. Schmid. Wave impeding block (WIB) for response reduction of soil-structure under train induced vibrations. 10th European Conference on Earthquake Engineering. In: Duma (ed.). Balkema, Rotterdam, 1995.
[16] A.T. Peplow and A.M. Kaynia. Prediction and validation of traffic vibration reduction due to cement column stabilization. Soil Dynamics and Earthquake Engineering, 27, 793–802, 2007.
[17] X. Sheng, C.J.C. Jones, and D.J. Thompson. Prediction of ground vibration from trains using the wavenumber finite and boundary element methods. Journal of Sound and Vibration, 293(3–5), 575–586, 2006.
[18] M. Schevenels, S. François, and G. Degrande. EDT: An ElastoDynamics Toolbox for MATLAB. *Computers & Geosciences*, 35(8):1752-1754, 2009.