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Railway Induced Vibration Abatement Solutions

Collaborative project

Results of the parameter studies and prioritization for prototype construction for slab track

Deliverable D3.3

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1. EXECUTIVE SUMMARY

Slab tracks with wide sleepers on under sleeper pads have been investigated in a parameter study using a finite-element boundary-element method. The slab track is modelled in detail by the finite element method. The infinite soil is modelled by the boundary element method as a homogeneous half-space. The track-soil system is coupled with a rigid wheelset mass so that the vehicle-track interaction is included. Transfer functions are calculated in frequency domain without and with vehicle-track interaction, the compliance of the track and the mobilities of the soil at different distances from the track. Finally, the ratios between the ground vibration amplitudes with and without mitigation measure are calculated to quantify the effectiveness of the mitigation measure.

A slab track with an under sleeper pad of a stiffness of $k_S = 50\ 10^6$ N/m, which can also be expressed as a stiffness per area of $k_S'' = 3.6\ 10^7$ N/m^3 = 0.036 N/mm^3, yields a vehicle-track resonance frequency of 32 Hz. Whereas the vibration at this frequency are amplified, higher frequencies are reduced. The insertion loss of this solution is up to 25 dB at 80 Hz for the ground vibrations in comparison to the reference slab track system (GETRAC system without sleeper pads but with soft rail pads).

The stiffness of the under sleeper pad has a strong influence on the vibration reduction. The softest sleeper pad yields the lowest vehicle-track resonance frequency and the best reduction of the ground vibration. The influence of other parameters has been examined, such as the stiffness of the rail pads, the stiffness of the slab material, the stiffness of the sleeper material, and the distance between the sleepers. All these parameters show no or only a minor influence on the mitigation effect.

As a conclusion, a wide sleeper slab track with under sleeper pads is recommended for further testing with under sleeper pads as soft as possible and with the highest possible sleeper mass. The stiffness of the rail pads can be chosen according to acoustical requirements.

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3. INTRODUCTION

Train-induced vibrations are becoming a growing problem all over Europe. The European research project “Railway induced vibration abatement solutions (RIVAS)” is focussed on measures to be applied at the source, at the track, in the transmission and propagation path and at the vehicles. The work package 3 “Mitigation measures track” includes the task 3.4 which is concerned with “Mitigation measures for slab track” [9]. A combined finite-element boundary-element model is used to investigate the vibration reduction potential of different solutions. The influence of the following components, sleeper pads, rail pads, sleeper and slab stiffness, and the sleeper distance is analysed.

The comparison of different slab track systems will be given in Deliverable 3.11 whereas the present report concentrates on a particular slab track, the GETRAC system with under sleeper pads (Figure 16-1). The GETRAC system is characterised as a pre-stressed mono-block sleeper equipped with an under sleeper pad and laid on a stiff asphalt slab. The wide sleepers of this slab track system provide a higher elastically supported mass than other slab track systems (e.g. Sonneville LVT). The higher sleeper mass has been identified as beneficial for the vibration abatement in Deliverable 3.2.

Tracks with under sleeper pads have been investigated in a wide parameter study in Deliverable 3.2 for ballasted tracks [8]. It has been found that the parameters with the strongest influence on the reduction of ground vibration

- the stiffness of the under sleeper pad,
- the mass of the sleeper,
- and the width of the sleeper.

Other parameters, such as

- the stiffness of the rail pads,
- the bending stiffness of the track,
- the stiffness of the ballast,
- the sub-soil, the soil, and the layering of the soil

showed no or only a minor influence on the mitigation effect. Most of these results can also be used for the slab track considered in this report. These parameter variations are not repeated here, but some more parameters such as

- the stiffness of the rail sleeper pad,
- the stiffness of the sleeper,

- the stiffness of the slab,
- and the distance between the sleepers

are checked for their influence on the mitigation of ground vibrations.

The structure of the report is as follows. The summary, table of content and introduction are numbered as sections 1, 2, and 3. Section 4 describes the methods of calculation using the available references, the finite element method for the track, the boundary element method for the infinitely extended soil, and the interaction with a rigid body model of the vehicle. Section 5 gives an overview on the parametric study. Section 6 presents the results for the reference track, Section 7 the results for the isolated slab tracks on different sleeper pads, and Section 8 the results of the parameter variations. The effectiveness of the mitigation measures is evaluated by the ratio of the ground vibrations for the isolated slab track and the reference track. Section 9 presents the conclusions.

4. METHODS OF VEHICLE-TRACK-SOIL INTERACTION

4.1 FINITE-ELEMENT BOUNDARY-ELEMENT METHOD

The track-soil systems are modelled by the combined finite-element boundary-element method [1, 5, 7]. The track including the rails, rail pads, sleepers, under sleeper pads, and the slab is modelled by the finite element method whereas the infinitely extended soil is modelled by the boundary element method. The dynamic stiffness matrix of the soil is established by using the Green's functions of an elastic layered half-space [3, 7]. All calculations (Green's functions, boundary matrix and finite element matrices) are performed in frequency domain. Special additional methods (within the FEBEM) have been developed for infinite tracks [6] which are also applied to this study.

The results of a FEBEM calculation are the frequency-dependent compliance u_R/F_T of the track (rail displacements u_R divided by the dynamic harmonic wheelset load F_T on the track) and mobility v_i/F_T of the soil (ground particle velocity divided by the dynamic harmonic wheelset load F_T on the track).

4.2 VEHICLE-TRACK INTERACTION

The influence of the vehicle on the ground vibration can be calculated in a second step in frequency domain as well [4]. The compliance of the track is inverted to the track stiffness $K_T = (u_R/F_T)^{-1}$. A corresponding dynamic stiffness K_V of the vehicle can be calculated by multi-body dynamics [2]. It can be approximated by the inertia of the wheelset $K_V = -m_W\omega^2$ in the frequency range of interest. The vehicle is excited by the irregularities s of the track (alignment and rail roughness) and the vehicle (out-of-roundness and roughness of the wheel).

The transfer function between the irregularities s and the force F_T on the track can be calulated as

$$\frac{F_T}{s} = -\frac{K_T K_V}{K_T + K_V}$$

The vehicle-track interaction can also be expressed as

$$\frac{F_T}{F_V} = \frac{K_T}{K_T + K_V}$$

if the force $F_V = -K_V s$ is used which is generated by the vehicle and the irregularities in case of a rigid track.

After the vehicle-track interaction is solved, the ground vibration can be calculated by multiplying the vehicle-track transfer function and the mobilities of the soil

$$\frac{v_i}{F_V} = \frac{v_i}{F_T}\frac{F_T}{F_V} = \frac{v_i}{F_T}\frac{K_T}{K_T + K_V}.$$

At the end, two different tracks (isolated and un-isolated track) are compared by comparing the vibration at the same soil point x_i. The velocity ratio $v_{i,U}/v_{i,I}$ of the un-isolated and isolated track can be built by the transfer functions without specifying the excitation

$$\frac{v_{i,U}}{v_{i,I}} = \frac{\dfrac{v_{i,U}}{F_V}}{\dfrac{v_{i,I}}{F_V}} = \frac{\left(\dfrac{v_i}{F_T}\dfrac{K_T}{K_T + K_V}\right)_{,U}}{\left(\dfrac{v_i}{F_T}\dfrac{K_T}{K_T + K_V}\right)_{,I}}.$$

4.3 VALIDATION OF THE METHODS

The present methods of track dynamics and vehicle-track interaction have been used since 1982 [10] for many reports and publications. They have been verified by comparison with other methods [11] and with several measurements [2, 4, 5, 10].

The methods are used for a single fixed axle load, not for moving train sets. This is sufficient to determine the frequency-dependent efficiency of the mitigation measures to reduce the ground response to dynamic loads. Effects on the excitation of the ground vibration such as reduced track errors and a reduced stiffness variation (parametrical excitation) are not discussed here, see [2, 4] for corresponding methods and results. Additional software tools have been developed by BAM for the prediction of railway induced vibration.

5. PARAMETER STUDY

5.1 MODEL OF THE TRACK AND THE VEHICLE

Figure 11-1 to Figure 11-3 show the finite element model of the track which has a length of 6.68 m. It consists of two rails, eleven sleepers with rail pads and under sleeper pads, a slab, and the infinite soil. End elements at the rails approximate the behaviour of an infinite track. The track is excited by a dynamic harmonic axle load (a pair of vertical forces) which acts on the rails above the central sleeper.

The only vehicle parameter is

the wheelset mass m_W = 1500 kg

5.2 PARAMETERS OF THE TRACK

A slab track with wide sleepers on under sleeper pads with the following parameters is analysed:

bending stiffness of the rails (UIC60)	EI = 2 x 2.1 10^{11} x 3.0 10^{-5} Nm^2 = 12.6 10^6 Nm^2,
mass per length of the rails	m'_R = 2 x 60 kg/m,
distance of the rail pads	d = 0.6 m
stiffness of the rail pads	k_R = 300 10^6 N/m,
modulus of elasticity of the sleepers	E_S = 3 10^{10} N/m^2,
mass density of the sleepers	ρ_S = 2.5 10^3 kg/m^3,
length of the sleepers	a_S = 2.6 m,
height of the sleepers	h_S = 0.2 m,
width of the sleepers	b_S = 0.52 m ,
stiffness of the sleeper pads	k_S = 50 10^6 N/m,
width of the slab	a_{B1} = 3.2 m,
height of the slab	h_B = 0.3 m,
elasticity modulus of the slab	E_P = 4 10^9 N/m^2,

shear modulus of the soil $G = 8\ 10^7$ N/m^2,

shear wave velocity of the soil $v_S = 200$ m/s

mass density of the soil $\rho = 2\ 10^3$ kg/m^3,

Poisson's ratio of the soil $\nu = 0.33$,

hysteretic damping of the soil $D = 2.5$ %,

hysteretic damping of the elastic elements $D_P = D_S = 10$ %.

The following parameter variations are performed in this deliverable:

stiffness of the sleeper pads $k_S = 25, 50, 100, 200\ 10^6$ N/m,

stiffness of the rail pads $k_R = 300, 1000\ 10^6$ N/m,

elasticity modulus of the slab $E_P = 0.48, 1, 4, 10, 30\ 10^9$ N/m^2,

modulus of elasticity of the sleepers $E_S = 1.5, 3, 6\ 10^{10}$ N/m^2,

distance of the rail pads $d = 0.6, 0.65$ m.

More parameter variations, for example variations of the sub-soil, the soil, and the layering of the soil have been analysed in Deliverable 3.2 for ballasted tracks. The minor influence on the reduction of ground vibration could also apply for isolated slab tracks.

The stiffness of the under sleeper pads

$k_S = 25, 50, 100, 200\ 10^6$ N/m

can also be expressed as a stiffness per area

$k''_S = 18, 36, 72, 144\ 10^6$ N/m^3 or

$k''_S = 0.018, 0.036, 0.072, 0.144$ N/mm^3 (according to DIN 45673).

For real under sleeper pads, it must be observed that they have different stiffnesses for the high static load and the small additional dynamic loads. The dynamic stiffness values must be applied for the reduction of the ground vibration due to dynamic loads.

A slab track without sleeper pads is calculated as a reference slab track. The reference slab track has the same parameters as given before but it has no under sleeper pads. The stiffness of the rail pads is taken as

$k_R = 40\ 10^6$ N/m,

so that the reference slab track has a realistic compliance. (In addition, the reference ballast track of Deliverable 3.2 is used in Appendix D to facilitate more comparisons.)

5.3 OUTPUT QUANTITIES

The following quantities are presented as the results of the track-soil and the vehicle-track interaction:

The compliance u_R/F_T or u_R/F_V of the track, without and with vehicle-track interaction,

the mobility v_i/F_T or v_i/F_V of the soil at 4, 8, 16, and 32 m from the centre of the track, without and with vehicle-track interaction,

and the ground vibration ratios $v_{i,U}$ /$v_{i,I}$ (insertion loss of the slab track with under sleeper pad) at 4, 8, 16, and 32 m from the centre of the track.

All ground vibration ratios $v_{i,U}$ /$v_{i,I}$ and all ground vibrations (mobilities v_i/F) in Appendix C and E are calculated with vehicle-track interaction.

6. RESULTS FOR THE REFERENCE TRACK

At first, the results of the FEBEM calculation without any vehicle-track interaction are shown in Figure 12-1a. The track compliance is almost constant at $u_R/F_T = 6\ 10^{-9}$ m/N for all frequencies. That means a rail displacement of 0.6 mm under a 100 kN axle load. At frequencies higher than 100 Hz, a weak increase of the compliance is observed. The mobilities of the soil (Figure 12-2a) show some characteristic changes in the frequency range of interest. At first, the soil mobilities increase with frequency up to 40 Hz. At higher frequencies, the mobilities turn to be constant or decreasing which is due to the material damping of the soil, which has its strongest effect on the far-field points of the soil, and due to the distribution of the excitation force across the track.

The compliance of the track and the dynamic stiffness of the vehicle (wheelset) yield the vehicle-track transfer function. The compliance of the track is multiplied by this vehicle track transfer function in Figure 12-1b, and including the vehicle track interaction yields considerably different results. Due to the soft rail pads of the reference track, a clear vehicle-track resonance can be observed at 50 Hz and a strong reduction of rail displacements at higher frequencies. The soil mobilities are multiplied by the vehicle-track transfer function in Figure 12-2b, and the soil mobilities at 4, 8, 16, and 32 m show the same vehicle-track resonance at 50 Hz and the strong decrease at higher frequencies as the rail compliance with vehicle-track interaction.

7. RESULTS FOR SLAB TRACKS WITH WIDE SLEEPERS ON SLEEPER PADS

The most important parameter to reduce the train induced ground vibration by under sleeper pads is the stiffness of the pads. The stiffness of the under sleeper pads is varied as k_S = 25, 50, 100, 200 10^6 N/m. Stiffer under sleeper pads are possible, but they have almost no positive effect below 100 Hz.

The softest under sleeper pad yields a track compliance higher than 0.01 mm/kN (1 mm per 100 kN axle load, Figure 13-1a). Stiffer under sleeper pads are below this value. All investigated under sleeper pads have track-pad resonances below 160 Hz, starting at 25 Hz for the softest and ending at 80 Hz for the stiffest sleeper pad. Including the wheelset mass yields a somewhat lower vehicle-track resonance frequency between 22 and 50 Hz (Figure 13-1b). The same lower resonance frequencies are found for the ground vibrations at the different distances (Figure 13-2 and Figure 13-3). The resonance amplification has lower values in case of stiffer sleeper pads. After the resonance, a strong decrease of the transfer functions is observed. The softest under sleeper pads yield the strongest reduction. The reduction is quantified by the ratio of the ground vibration of the reference track to the ground vibration of the slab track with sleeper pads (Figure 13-4 and Figure 13-5). These ratios (insertion losses) start at the value 1 (0 dB) at low frequencies. They decrease until the vehicle-track resonance of the isolated track is reached at 25 to 40 Hz. A strong increase follows up to 64 or 80 Hz where the maximum value of the insertion loss is found. At higher frequencies, the insertion loss varies around lower values. For the stiffness k_S = 50 10^6 N/m of the sleeper pad, the highest insertion loss is around 20 dB at 64 or 80 Hz. The maximum insertion loss is higher for the softest pad stiffness (20 to 30 dB) and lower for the stiffer sleeper pads. It is also higher for the far-field points where the sleeper pad of k_S = 50 10^6 N/m yields an insertion loss of 25 dB. The high insertion loss values are due to the resonance of the reference slab track and changes of the load distribution which have different effects at different distances from the track. Therefore, the insertion loss should be assured by using different observation points (Figure 13-4 and Figure 13-5) and different reference tracks (see Appendix D). The minimum of the insertion loss due to the vehicle-track resonance of the isolated track is smallest for the softest sleeper pad reaching a value of -10 dB.

8. COMPLEMENTARY RESULTS

The analyses in the following Sections have been done to check if the effectiveness of the under sleeper pads is influenced by certain parameters. The stiffness of the under sleeper pad is kept constant at k_S = 50 10^6 N/m.

8.1 VARIATION OF THE RAIL PAD STIFFNESS

In deliverable 3.2 of RIVAS [8], it has been found that a soft rail pad could give a worse efficiency of soft sleeper pads. Therefore, the isolated slab track is also calculated with a stiffer rail pad of k_R = 1000 kN/mm to check whether the rail pad of k_R = 300 kN/mm is already stiff enough to achieve the optimum effect of the under sleeper pad. As a result, the static displacement is reduced by 1 % if the stiff rail pads are used (Figure 15-1). Some small differences can be found at high frequencies for the track compliance as well as for the soil mobilities in Figure 15-2 and Figure 15-3, but there is no clear tendency that the stiffer rail pads can improve the mitigation.

8.2 VARIATION OF THE SLAB STIFFNESS

The slab material has been varied in a wide range. The elasticity modulus of three different asphalt materials has been chosen, and in addition a higher elasticity modulus (the elasticity modulus of concrete) and a lower elasticity modulus (comparable to the elasticity modulus of a stiff ballast) are taken in to account. The compliances of the tracks with different slab materials are identical (Figure 15-4). The differences are found for the ground vibration at high frequencies above 50 Hz (Figure 15-5 and Figure 15-6). The differences are usually in the order of the different elastic moduli, but the stiffest slab material yields at some frequencies the highest and at some frequencies the lowest value. A general tendency, that a stiffer slab material can improve the mitigation effect of the under sleeper pads, must be denied. A similar minor influence on the track and ground vibration might be expected for the slab mass.

8.3 VARIATION OF THE SLEEPER STIFFNESS

The elasticity modulus of concrete varies in certain limits. In the present report a wider range of stiffness values, 1.5 to 6 10^{10} N/m^2, has been examined to find clearer effects. Some small differences have been found in Figure 15-7 to Figure 15-9 for frequencies above 80 Hz. At 80 Hz, the stiffest material yields the highest amplitudes whereas at 160 Hz, the softest material has the highest amplitudes of the three materials. There is no clear order of amplitudes, and the differences vary with frequency. So it is concluded that there is an influence of the sleeper stiffness but without a clear advantage for the stiffer or softer material.

8.4 VARIATION OF THE SLEEPER DISTANCE

On Figure 15-10 to Figure 15-12 two sleeper distances are compared, d = 0.6 m and 0.65 m. The displacements above the sleeper differ by 4 %. The ground vibration curves are almost identical. So it is concluded that the small variation of the sleeper distance of less than 10 % yields only negligible changes in the behaviour and effectiveness of the under sleeper pads. The distance between the sleepers has an influence on the parametric excitation which has not been studied here.

9. CONCLUSION

Slab tracks with wide sleepers on under sleeper pads have been investigated in a parameter study using a finite-element boundary-element method. The influence of different parameters on the reduction of the ground vibration has been investigated.

- The stiffness of the under sleeper pad has a strong influence on the vibration reduction. The softest sleeper pad yields the lowest vehicle-track resonance frequency and the best reduction of the ground vibration. For example, the sleeper pad stiffness of $k_S = 50\ 10^6$ N/m yields a vehicle-track resonance frequency of 32 Hz and a maximum insertion loss of 25 dB at 80 Hz.

The influence of other parameters has been examined, such as

- the stiffness of the rail pads,
- the stiffness of the slab material,
- the stiffness of the sleeper material,
- and the distance between the sleepers.

All these parameters show no or only a minor influence on the mitigation effect.

These results are complementary to the results in Deliverable 3.2 for ballasted tracks on sleeper pads where

- the mass of the sleeper,
- and the width of the sleeper

showed a positive effect on the vibration reduction, and

- the stiffness of the sub-soil,
- the stiffness and the layering of the soil

showed no or only a minor influence on the mitigation effect.

As a conclusion, a wide sleeper slab track with under sleeper pads is recommended for further testing with under sleeper pads as soft as possible and with the highest possible sleeper mass. The stiffness of the rail pads can be chosen according to acoustical requirements.

10. REFERENCES

[1] L. Auersch, G. Schmid: A simple boundary element formulation and its application to wavefield excited soil-structure interaction. Earthquake Engineering and Structural Dynamics 19, 1990, 931-947.

[2] L. Auersch: Zur Parametererregung des Rad-Schiene-Systems: Berechnung der Fahrzeug-Fahrweg-Untergrund-Dynamik und experimentelle Verifikation am Hochgeschwindigkeitszug Intercity Experimental. Ingenieur-Archiv 60, 1990, 141-156.

[3] L. Auersch: Wave propagation in layered soil: theoretical solution in wavenumber domain and experimental results of hammer and railway traffic excitation. Journal of Sound and Vibration 173, 1994, 233-264.

[4] L. Auersch: The excitation of ground vibration by rail traffic: Theory of vehicle-track-soil interaction and measurements on high-speed lines. Journal of Sound and Vibration 284, 2005, 103-132.

[5] L. Auersch: Dynamics of the railway track and the underlying soil: the boundary-element solution, theoretical results and their experimental verification. Vehicle System Dynamics 43, 2005, 671-695.

[6] L. Auersch: Dynamic axle loads on tracks with and without ballast mats – numerical results of three-dimensional vehicle-track-soil models. Journal of Rail and Rapid Transit 220, 2006, 169-183.

[7] L. Auersch: Wave propagation in the elastic half-space due to an interior load and its application to ground vibration problems and buildings on pile foundations. Soil Dynamics and Earthquake Engineering 30, 2010, 925–936.

[8] L. Auersch: Mitigation measures for ballasted tracks – sleeper, sleeper pads and substructure – results from the finite-element boundary-element method. Appendix B in B. Faure, E. Bongini, BAM, KUL: Results of the parameter studies and prioritization for prototype construction for ballasted track. Deliverable 3.2 of RIVAS, 2012.

[9] „Railway Induced Vibration Abatement Solutions“, Description of Work. Collaborative project for theme SST.2010.1.1-3. “Attenuation of ground-borne vibration affecting residents near railway lines” in the seventh framework programme.

[10] W. Rücker: Dynamic interaction of a railroad-bed with the subsoil. Proc. Conf. Soil Dynamics and Earthquake Engineering. Southampton 1982, 435-448.

[11] W. Rücker, L. Auersch, M. Baeßler, K. Knothe, K. Popp, S. Savidis, G. Schmid: A Comparative Study of Results from Numerical Track-Subsoil Calculations. In: K. Popp, W. Schiehlen (eds.); Lecture Notes in Applied Mechanics “System Dynamics and Long-Term Behaviour of Railway Vehicles, Track and Subgrade”, Berlin: Springer-Verlag, 2003, 471-488.

11. APPENDIX A – THE TRACK MODEL

Rail
Rail pad
Sleeper
Sleeper pad
Slab

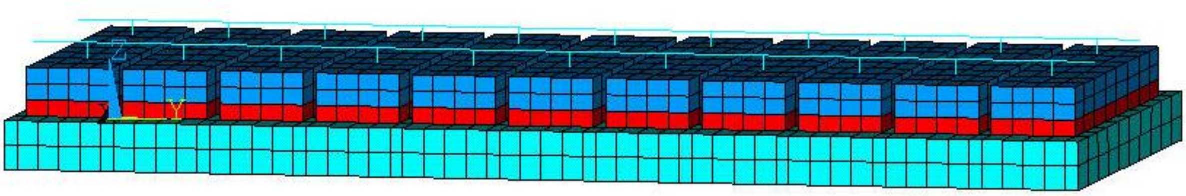


Figure 11-1: Finite-element-model of the slab track

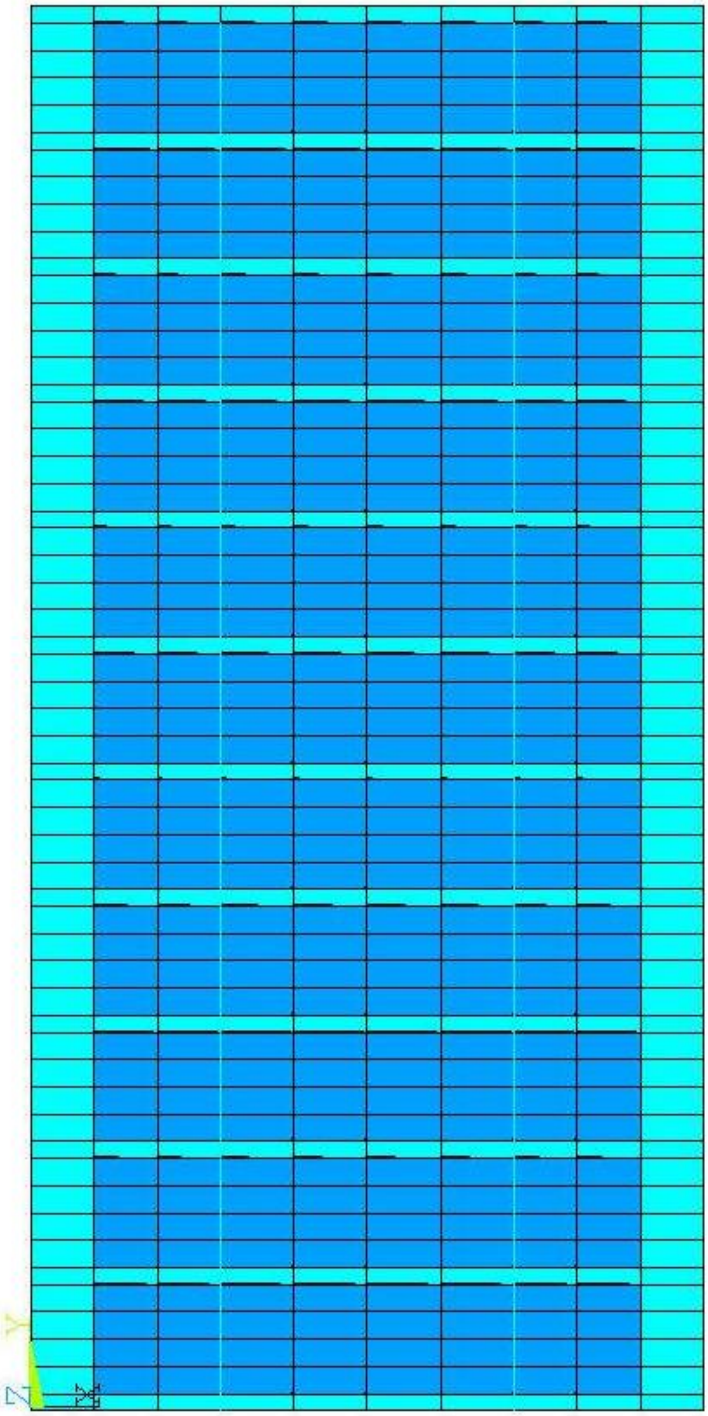


Figure 11-2: Finite-element-model of the slab track, top view

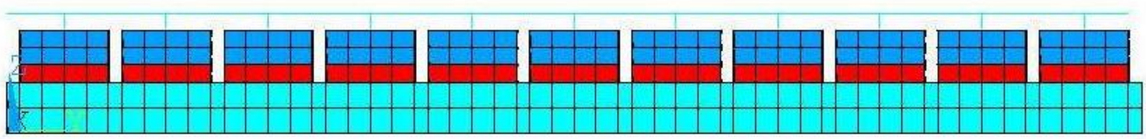


Figure 11-3: Finite-element-model of the slab track, view along and across the track

12. APPENDIX B – RESULTS OF THE REFERENCE SLAB TRACK

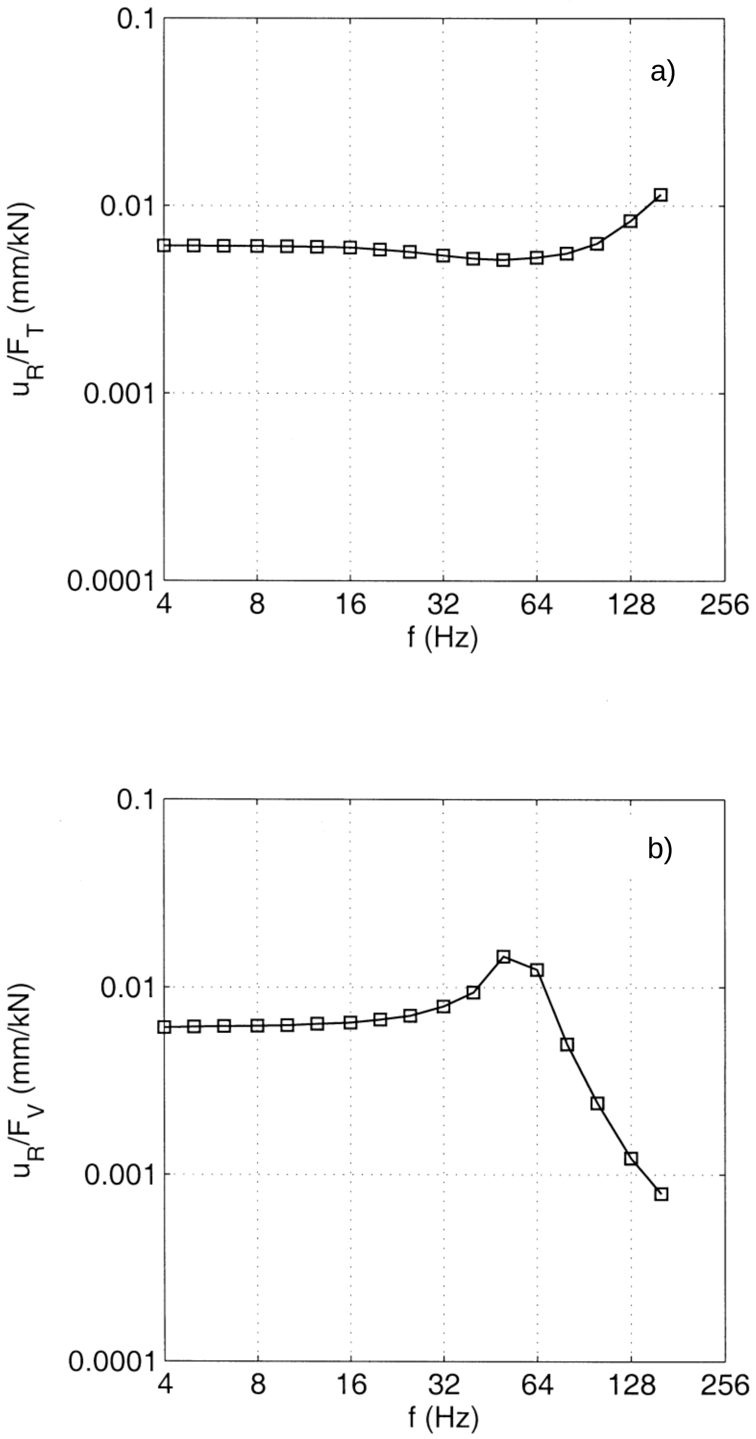


Figure 12-1: Reference track, compliance of the track a) without and b) with vehicle-track interaction

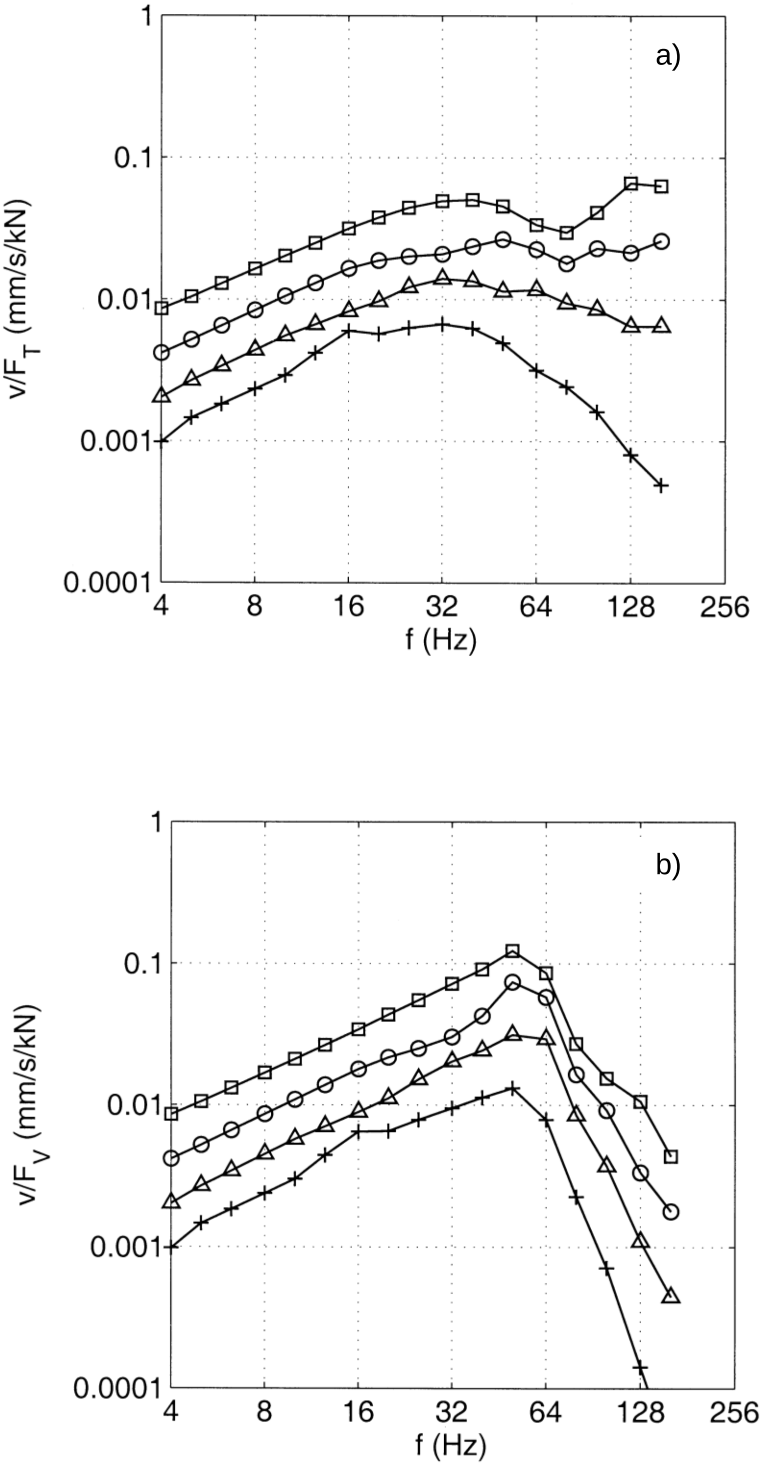


Figure 12-2: Reference track, mobilities of the soil at □ 4, ○ 8, △ 16, + 32 m, a) without and b) with vehicle-track interaction

13. APPENDIX C – RESULTS OF THE SLAB TRACK WITH DIFFERENT UNDER SLEEPER PADS

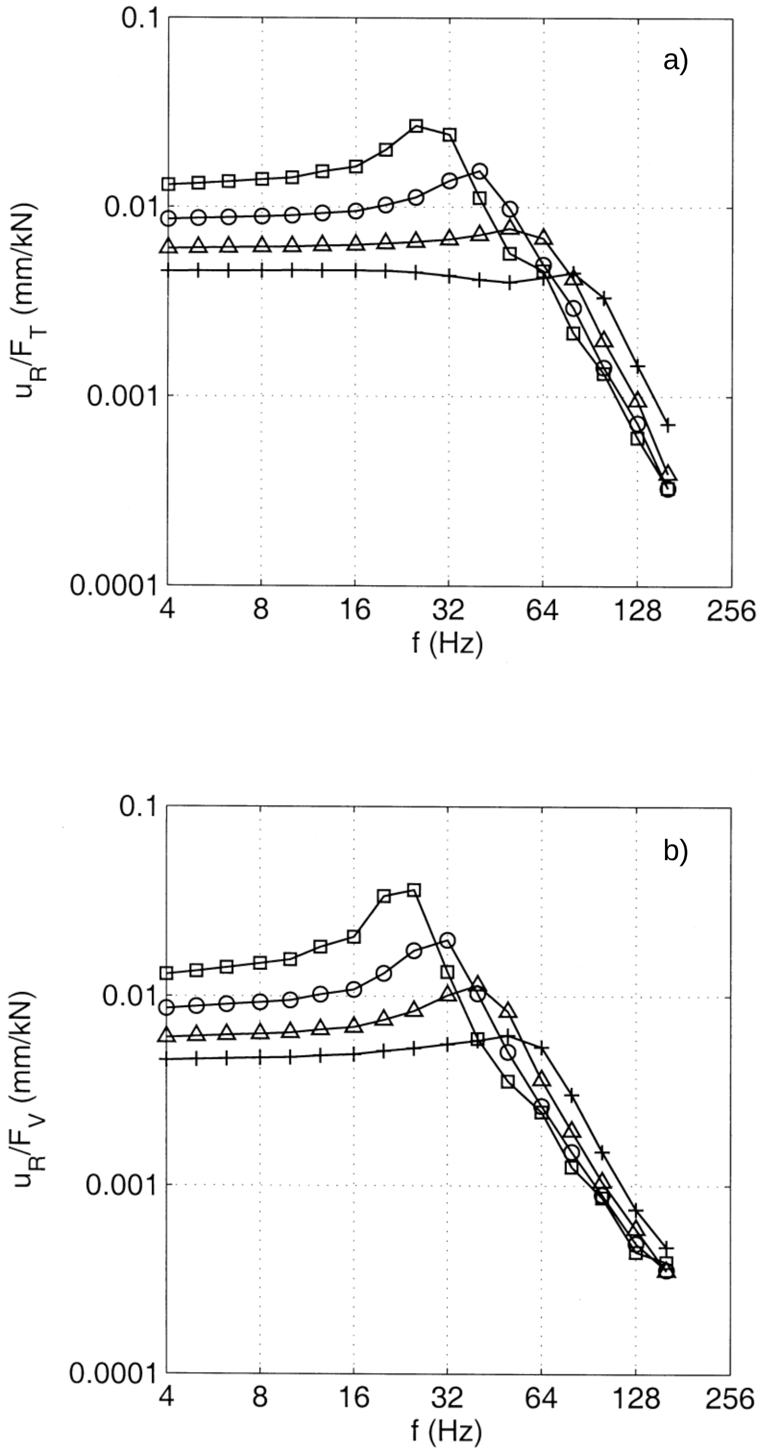
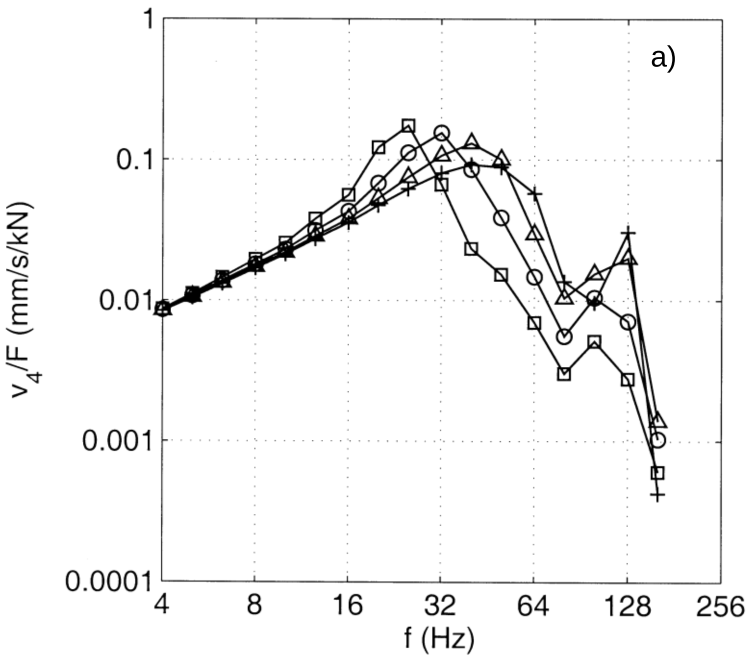


Figure 13-1: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, compliances of the track a) without and b) with vehicle-track interaction



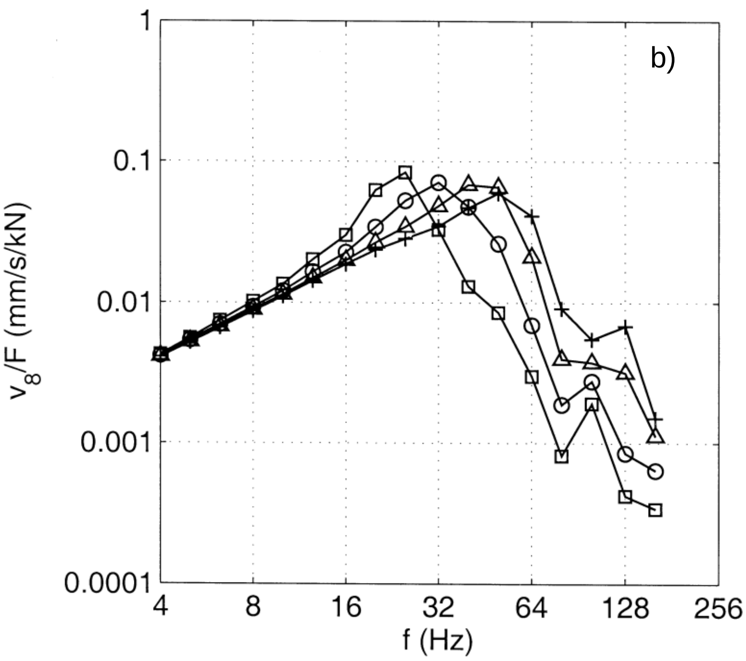


Figure 13-2: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, mobilities of the soil at a) 4, b) 8 m distance from the track, including vehicle-track interaction

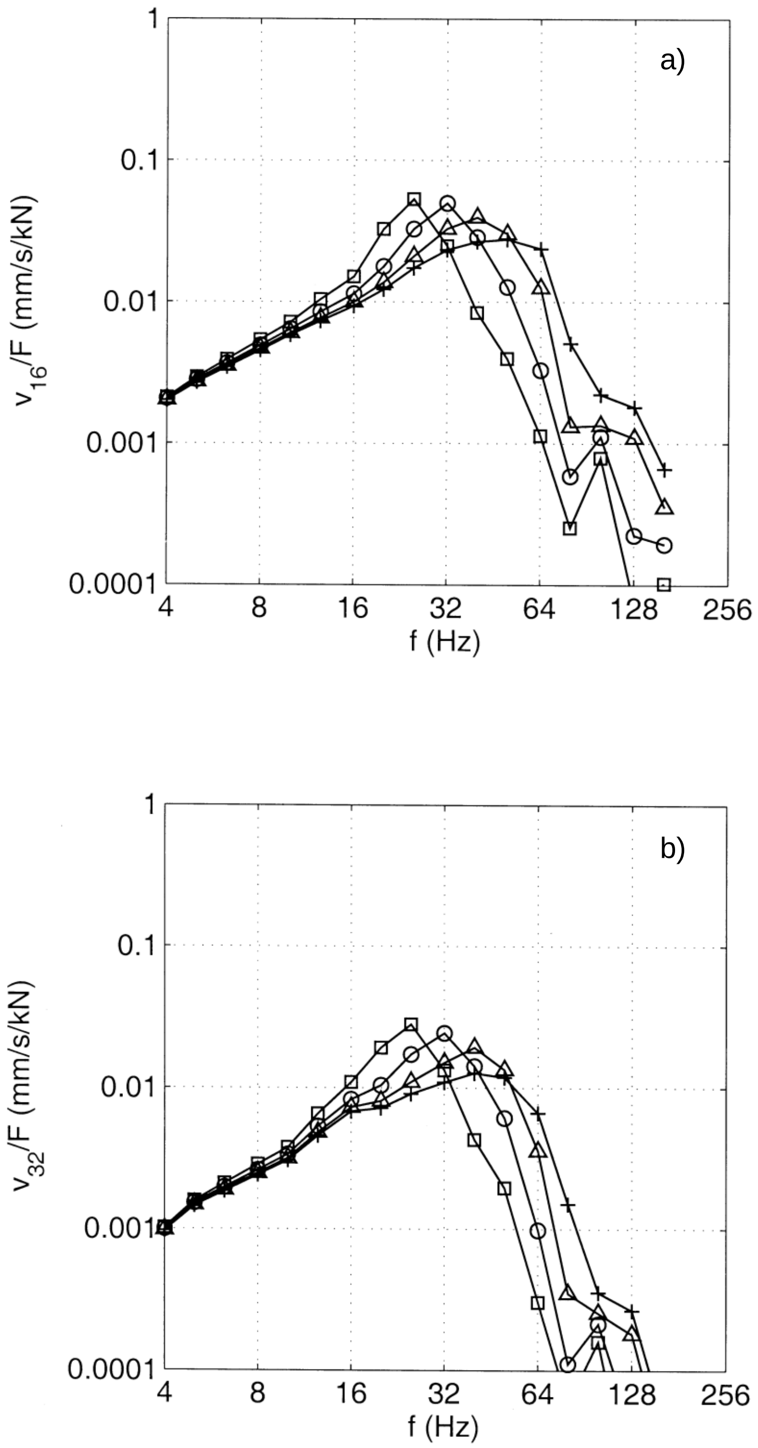


Figure 13-3: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, mobilities of the soil at a) 16, and b) 32 m distance from the track, including vehicle-track interaction

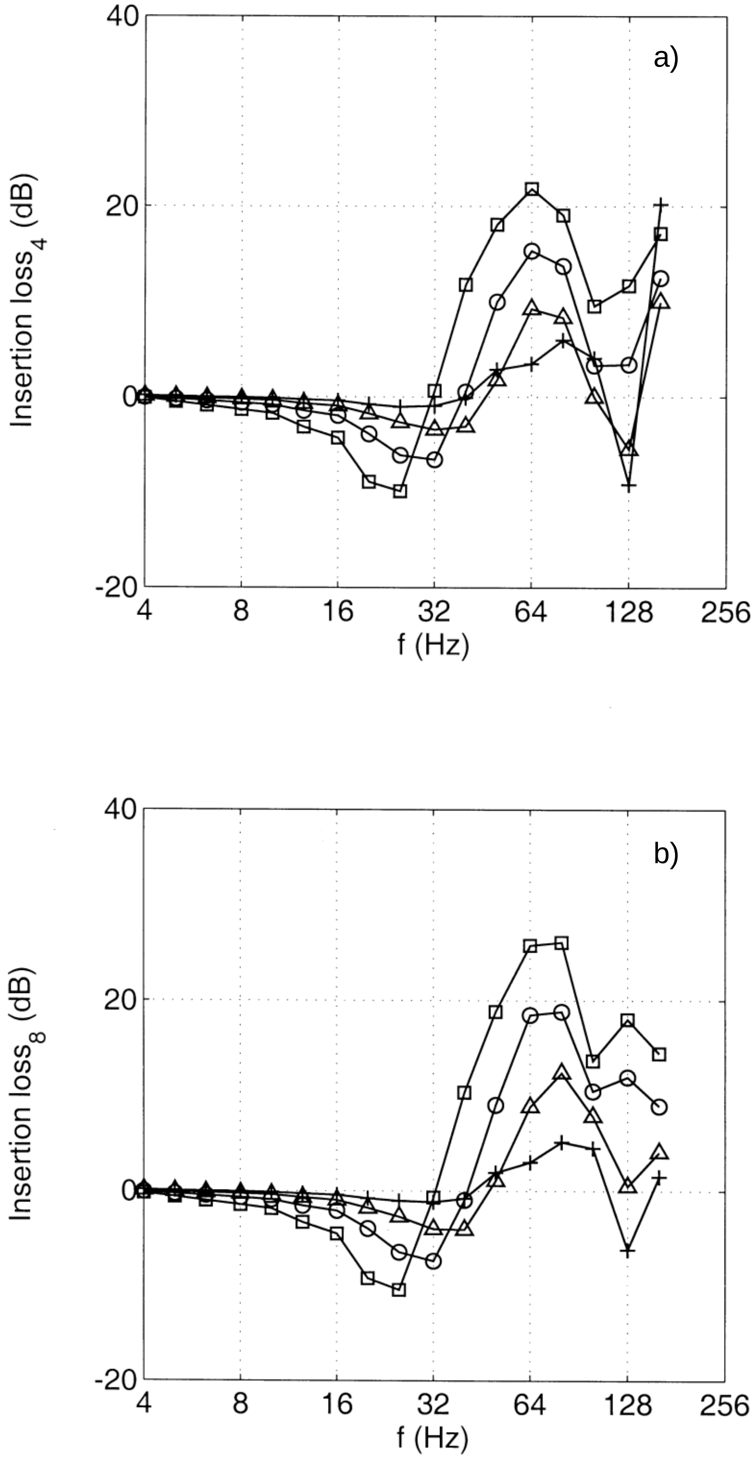


Figure 13-4: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, insertion loss (reference slab track divided by isolated slab track) of the ground vibration at a) 4, b) 8 m distance from the track

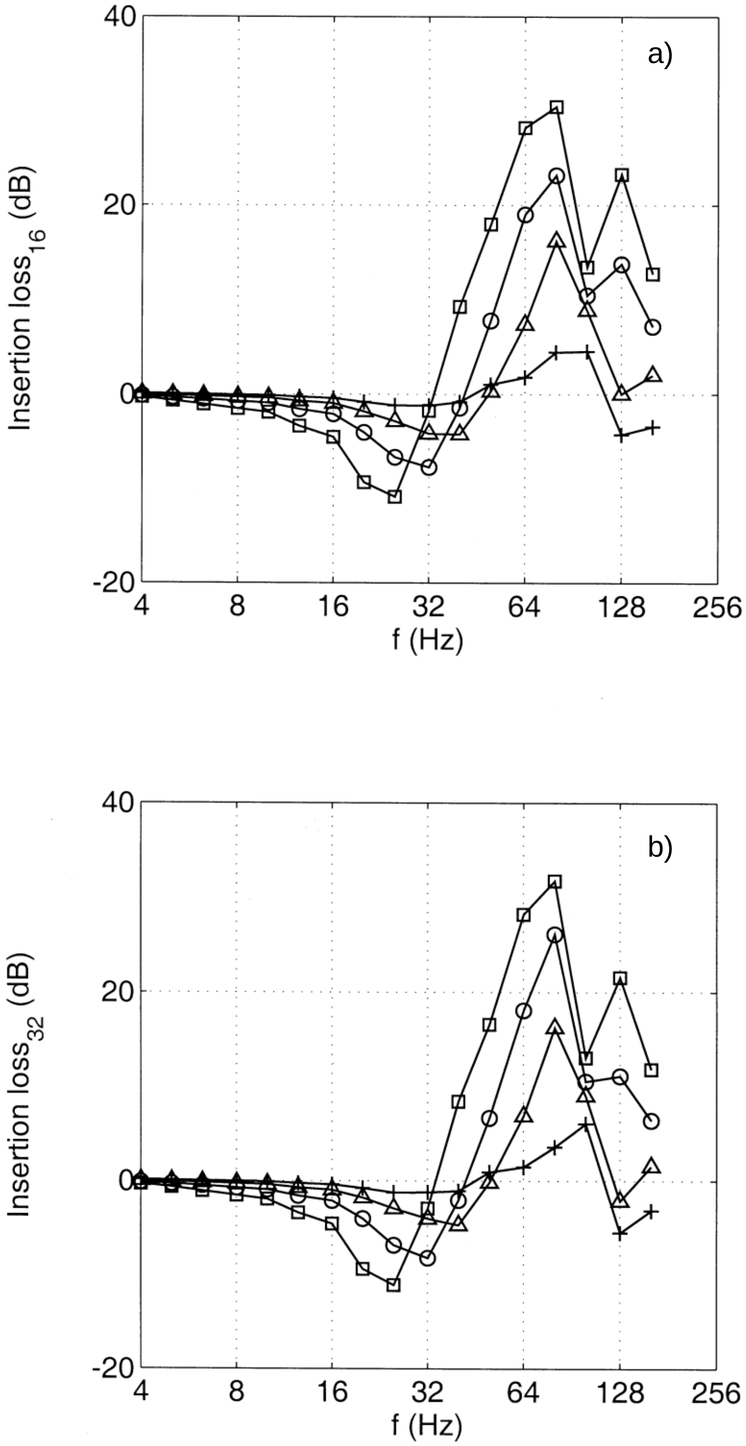
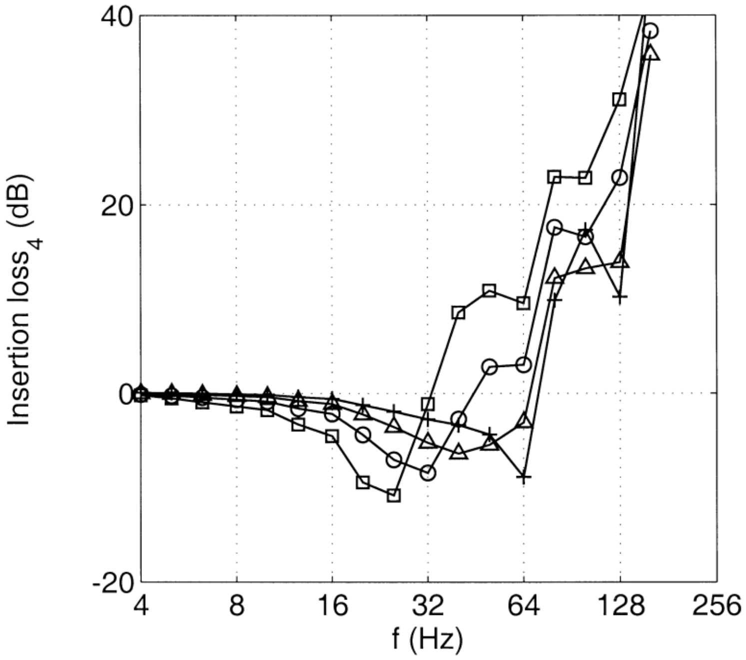


Figure 13-5: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, insertion loss (reference slab track divided by isolated slab track) of the ground vibration at a) 16, and b) 32 m distance from the track

14. APPENDIX D – INSERTION LOSS COMPARED TO THE REFERENCE BALLAST TRACK

The results for the slab track are additionally compared to the ballasted reference track which is defined in the deliverable 3.2 “Mitigation for ballasted tracks” [8].



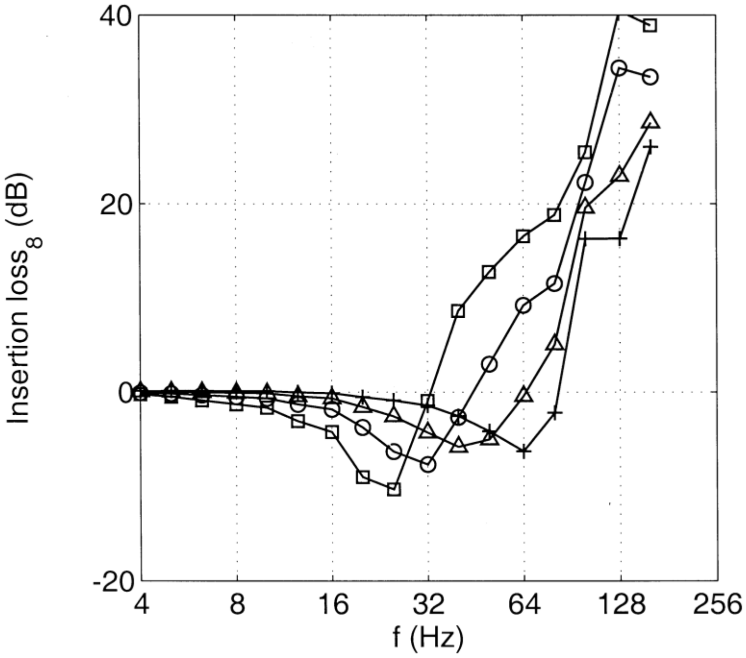


Figure 14-1: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, insertion loss (reference ballast track divided by isolated slab track) of the ground vibration at a) 4, b) 8 m distance from the track

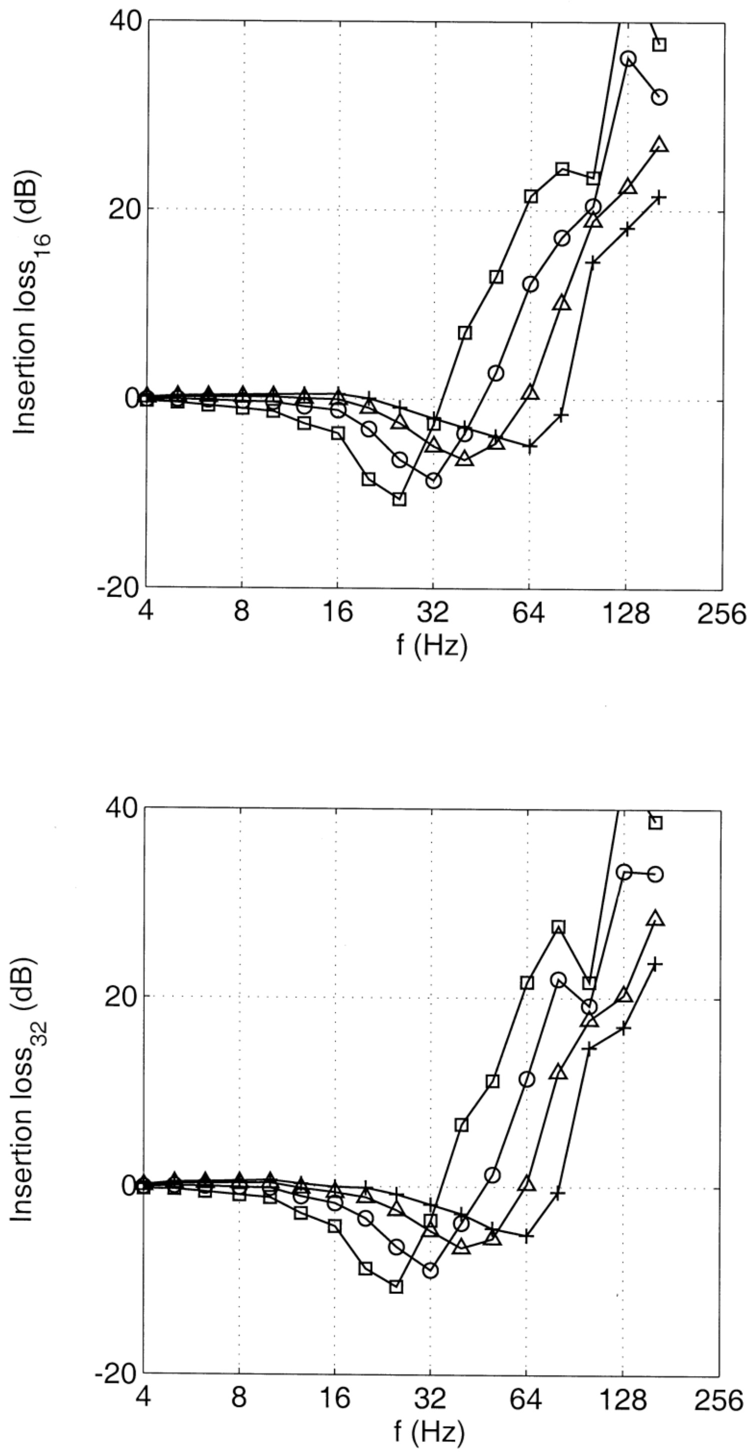
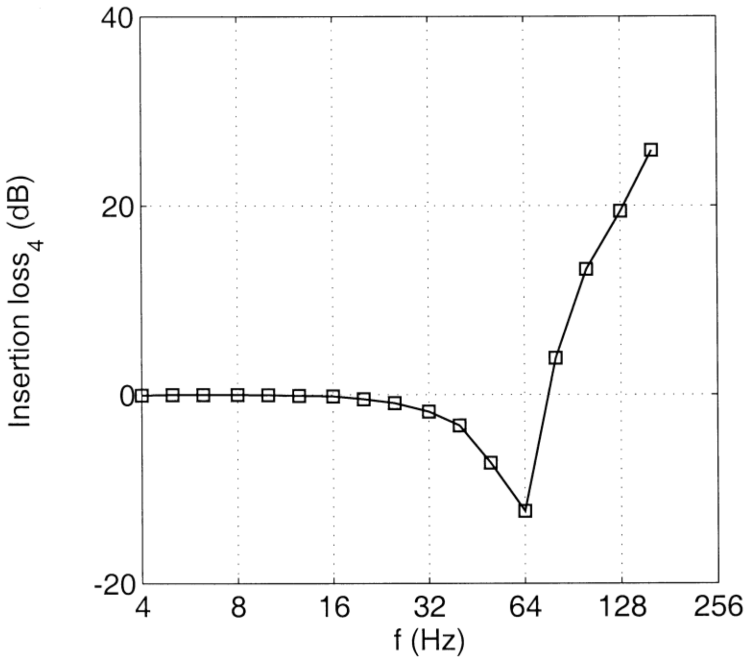


Figure 14-2: Slab tracks on different under sleeper pads, k_S = □ 25, ○ 50, △ 100, + 200 kN/mm, insertion loss (reference ballast track divided by isolated slab track) of the ground vibration at a) 16, b) 32 m distance from the track



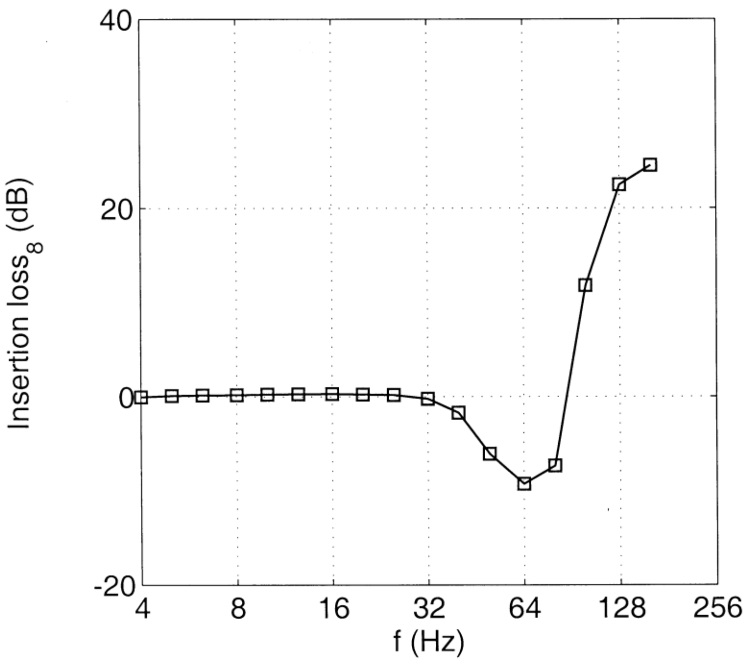


Figure 14-3: Reference slab track, insertion loss (reference ballast track divided by reference slab track) of the ground vibration at a) 4, b) 8 m distance from the track

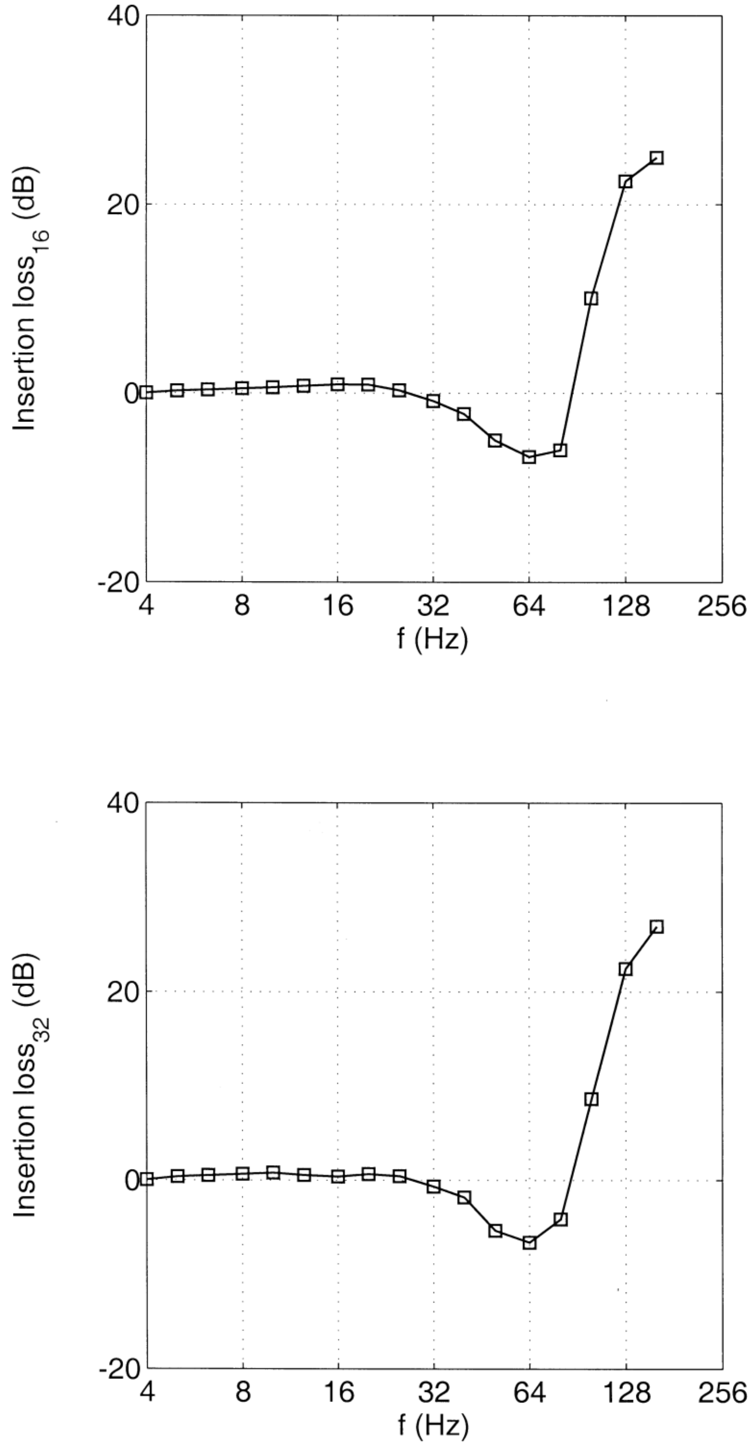
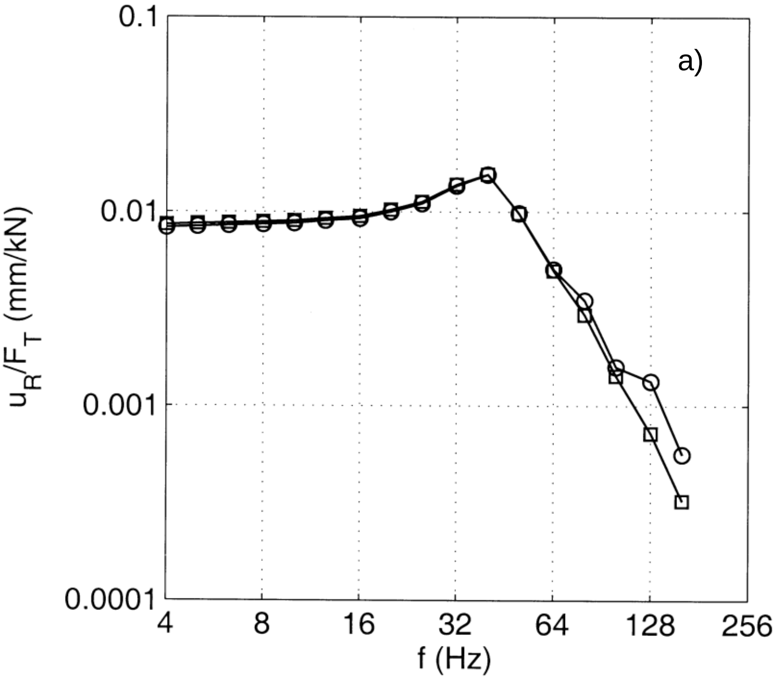


Figure 14-4: Reference slab track, insertion loss (reference ballast track divided by reference slab track) of the ground vibration at a) 16, b) 32 m distance from the track

15. APPENDIX E – COMPLEMENTARY RESULTS OF SLAB TRACKS WITH SLEEPER PADS OF 50 KN/MM



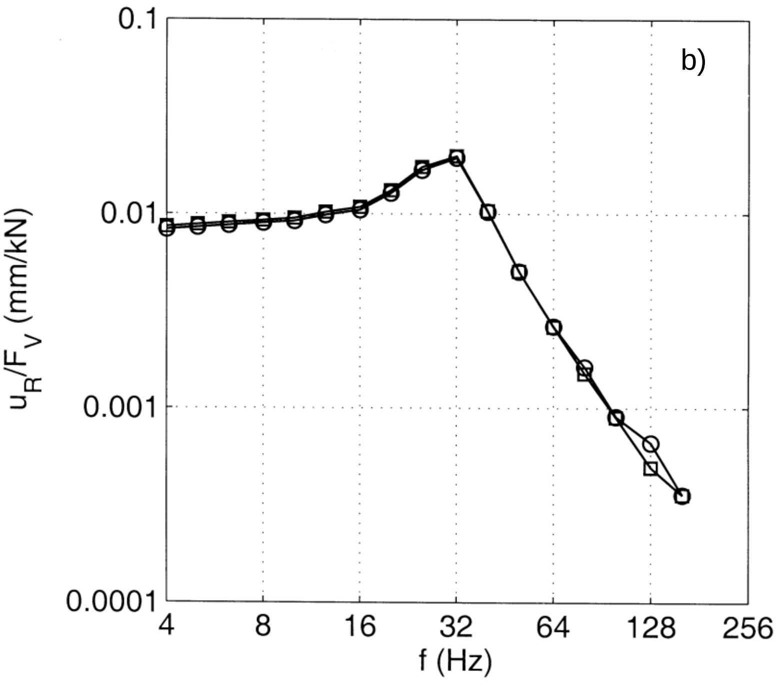


Figure 15-1: Tracks with different rail pads k_R = □ 300, ○ 1000 kN/mm, compliances of the track a) without and b) with vehicle-track interaction

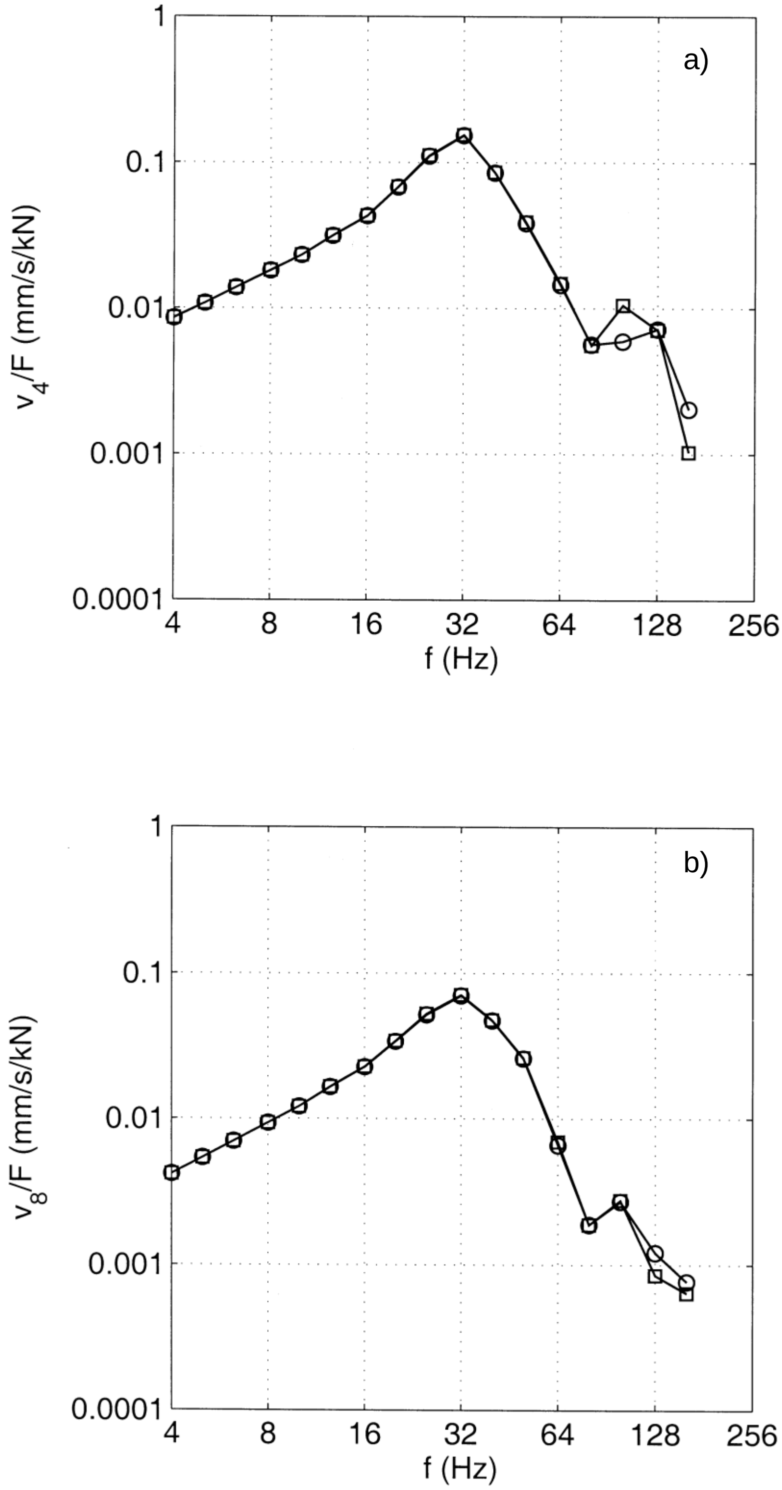
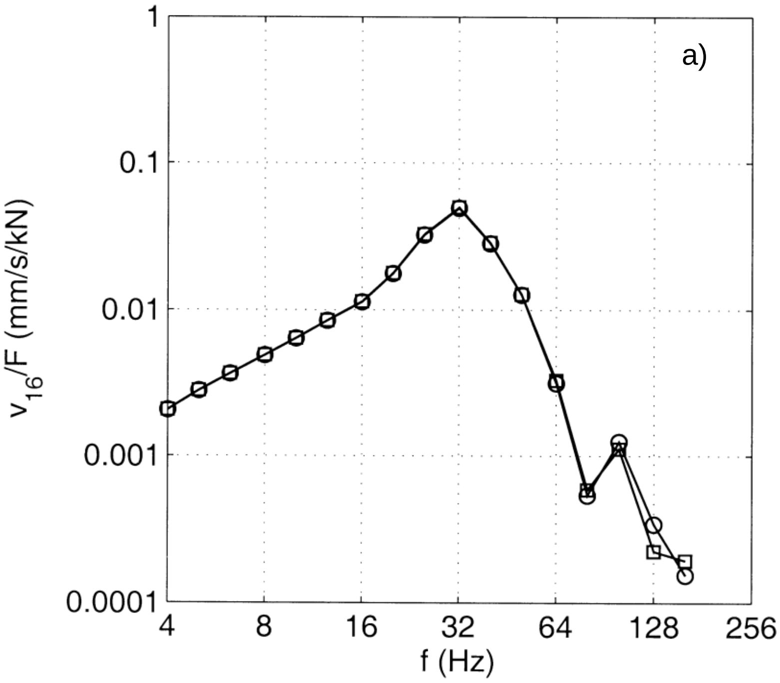


Figure 15-2: Tracks with different rail pads k_R = □ 300, ○ 1000 kN/mm, mobilities of the soil at a) 4, b) 8 m distance from the track, including vehicle-track interaction



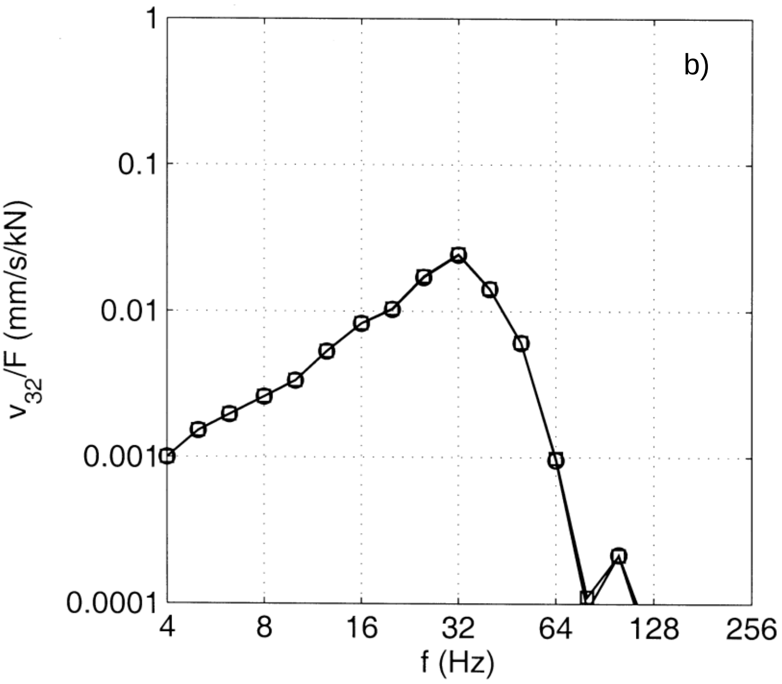
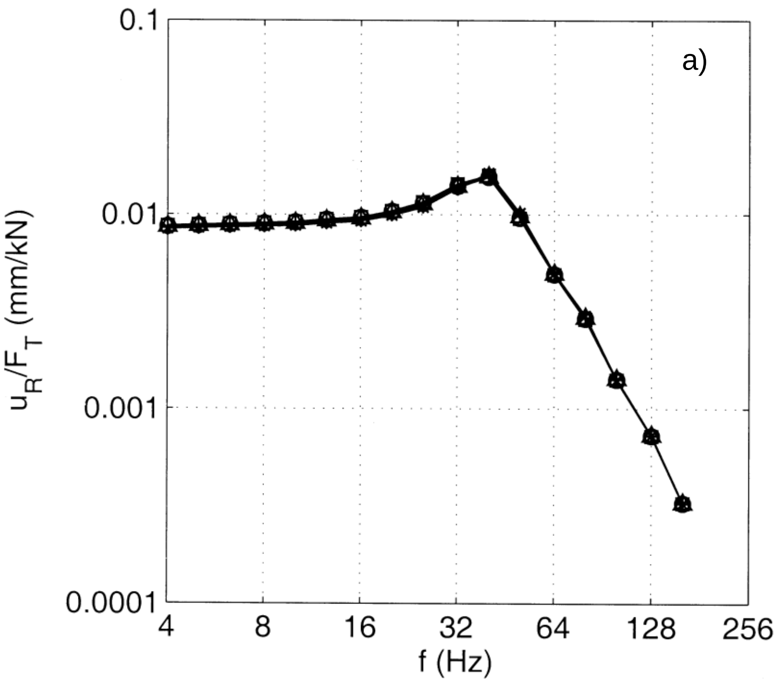


Figure 15-3: Tracks with different rail pads k_R = □ 300, ○ 1000 kN/mm, mobilities of the soil at a) 16, and b) 32 m distance from the track, including vehicle-track interaction



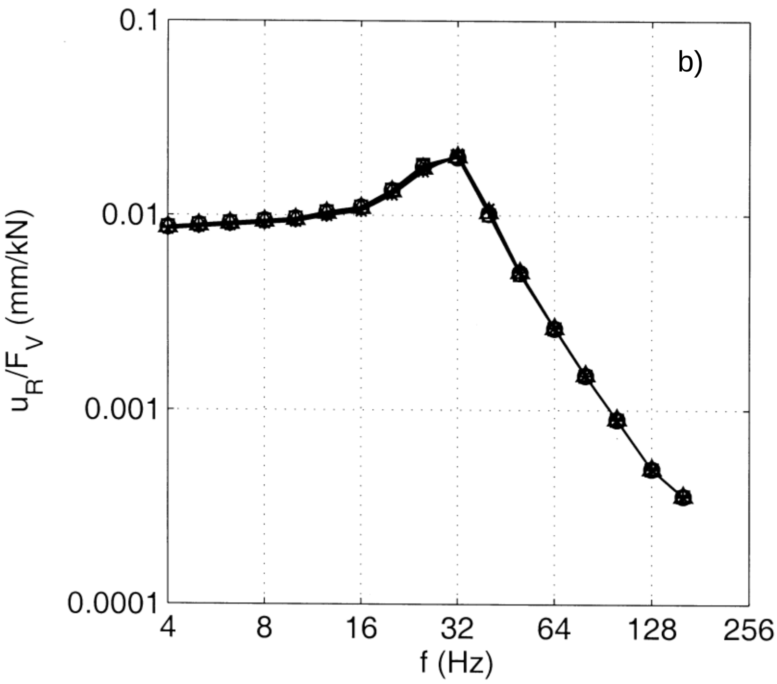
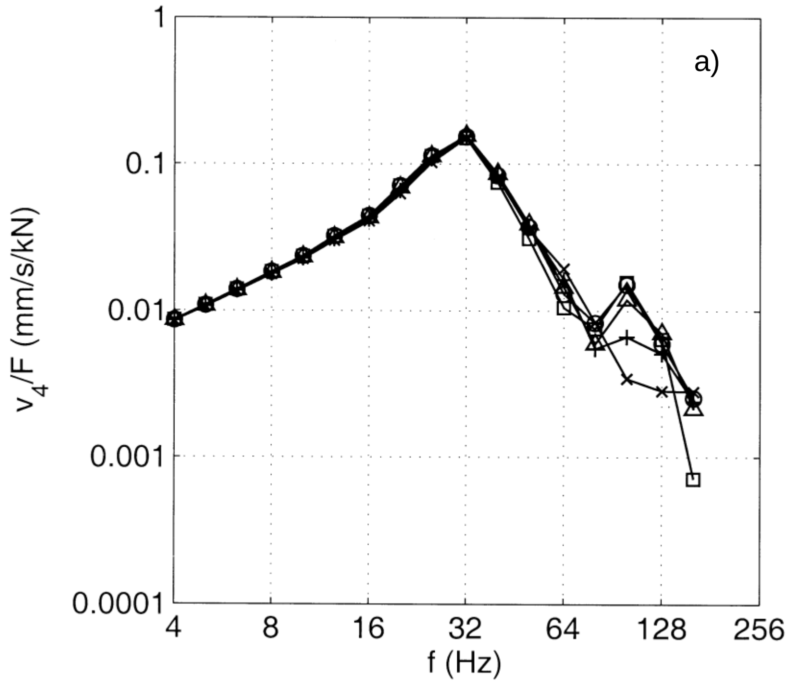


Figure 15-4: Tracks with different slab material E_P = □ 0.48, ○ 1, △ 4, + 10, × 30 10^9 N/m², compliances of the track a) without and b) with vehicle-track interaction



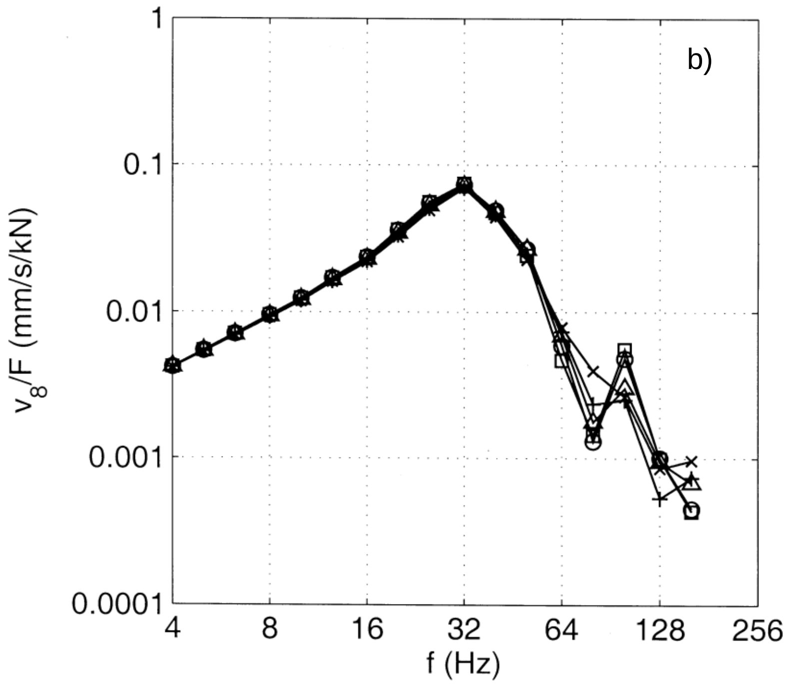
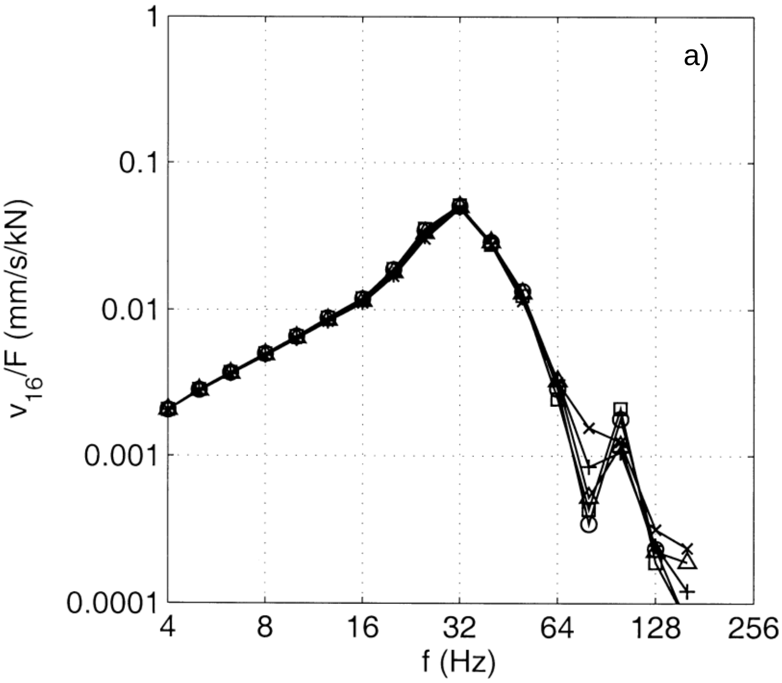


Figure 15-5: Tracks with different slab material E_P = □ 0.48, ○ 1, △ 4, + 10, × 30 10^9 N/m², mobilities of the soil at a) 4, and b) 8 m distance from the track, including vehicle-track interaction



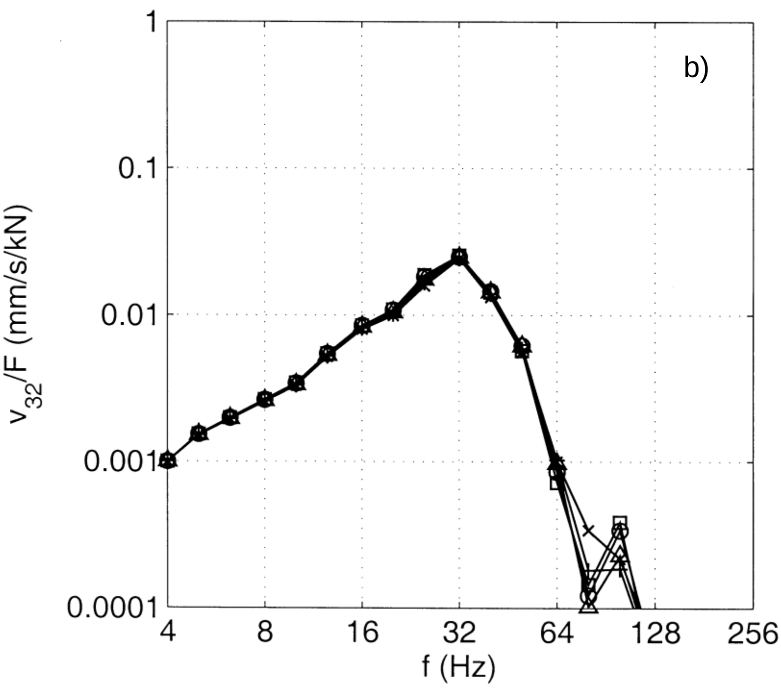


Figure 15-6: Tracks with different slab material E_P = □ 0.48, ○ 1, △ 4, + 10, × 30 10^9 N/m², mobilities of the soil at a) 16, and b) 32 m distance from the track, including vehicle-track interaction

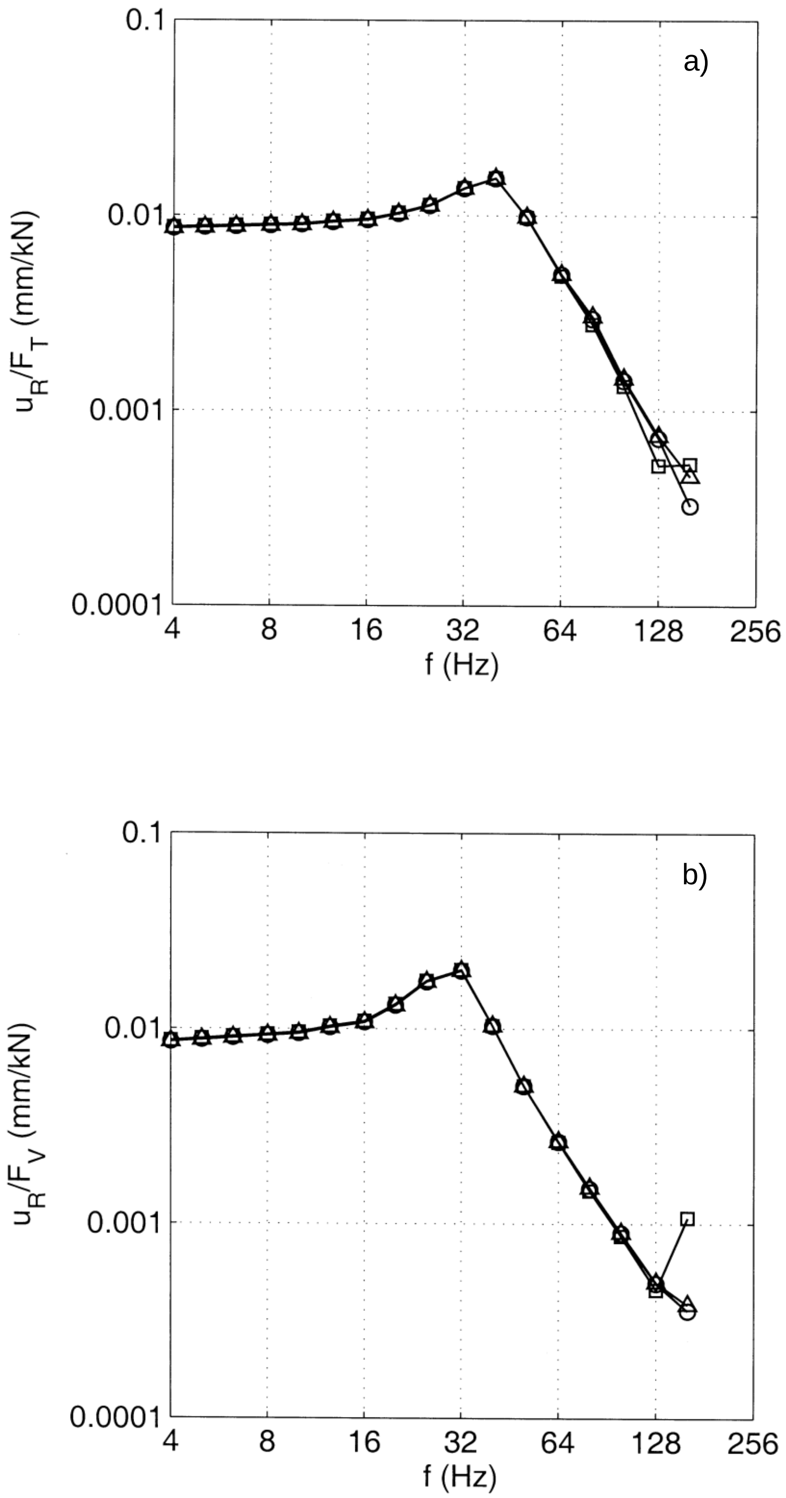


Figure 15-7: Slab tracks with different sleeper material E_S = □ 1.5, ○ 3, △ 6 10^{10} N/m^2, compliances of the track a) without and b) with vehicle-track interaction

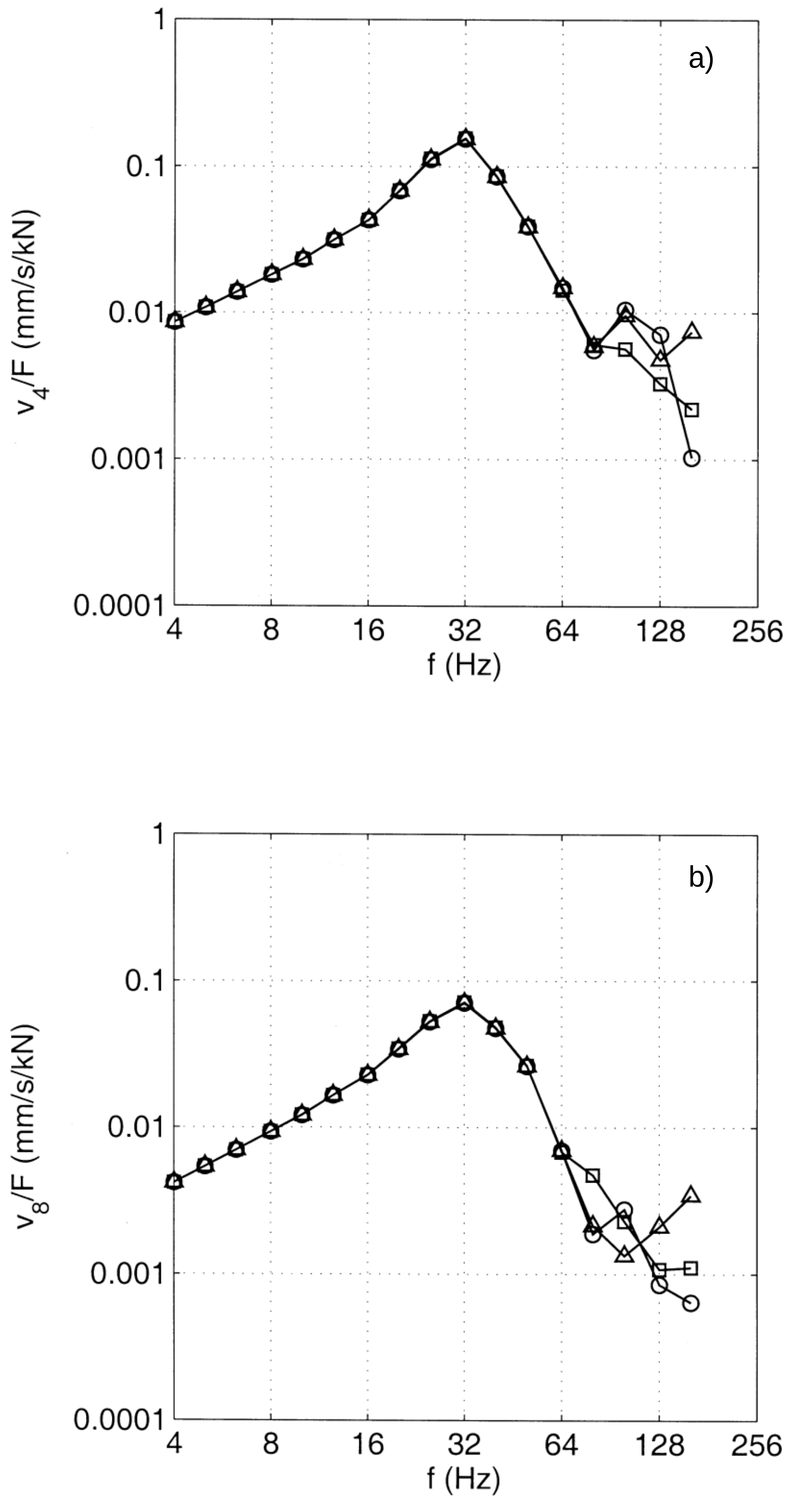


Figure 15-8: Slab tracks with different sleeper material E_S = □ 1.5, ○ 3, △ 6 10^{10} N/m^2, mobilities of the soil at a) 4, b) 8 m distance from the track, including vehicle-track interaction

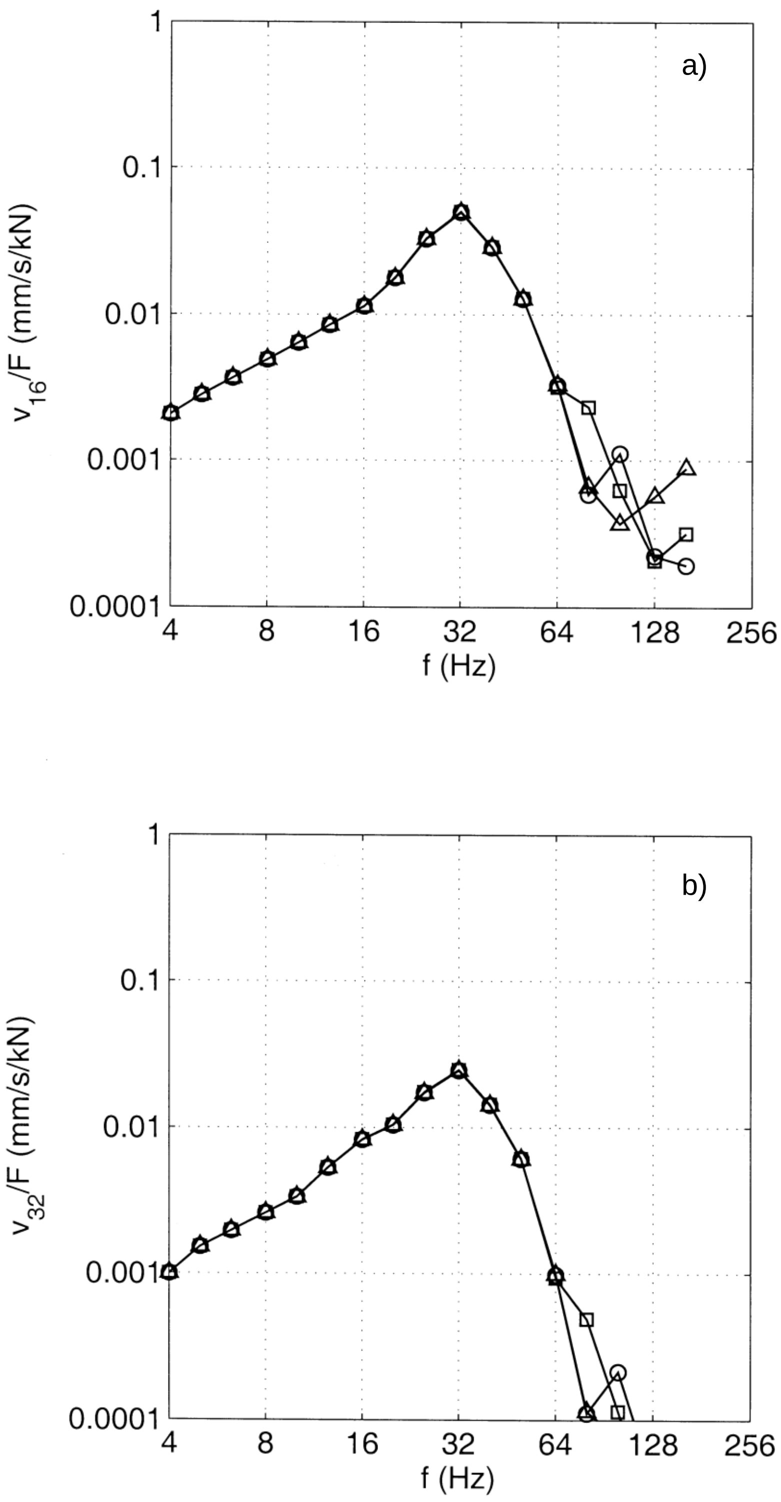


Figure 15-9: Slab tracks with different sleeper material E_S = □ 1.5, ○ 3, △ 6 10^{10} N/m^2, mobilities of the soil at a) 16, and b) 32 m distance from the track, including vehicle-track interaction

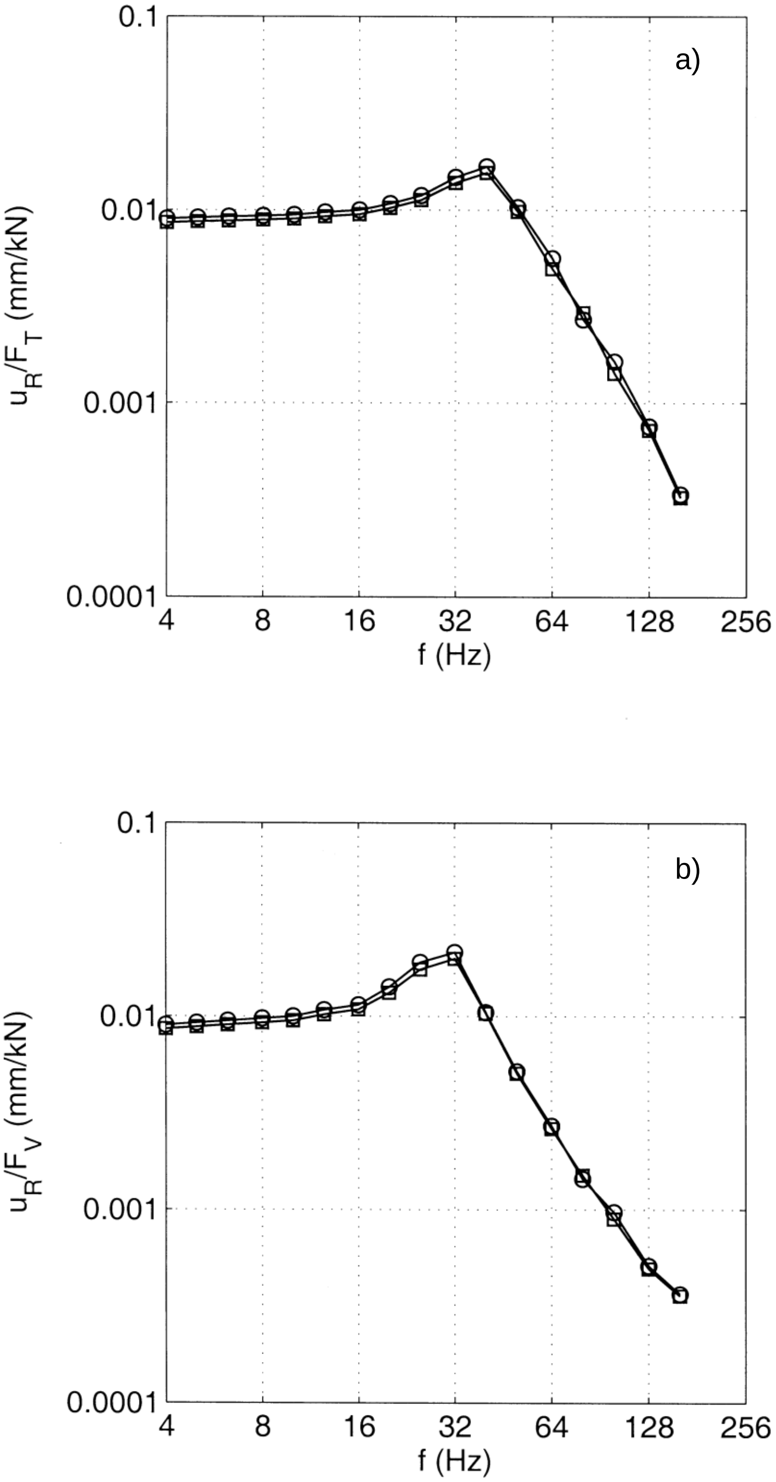


Figure 15-10: Slab tracks with different sleeper distances *d* = □ 0.6, ○ 0.65 m, compliances of the track a) without and b) with vehicle-track interaction

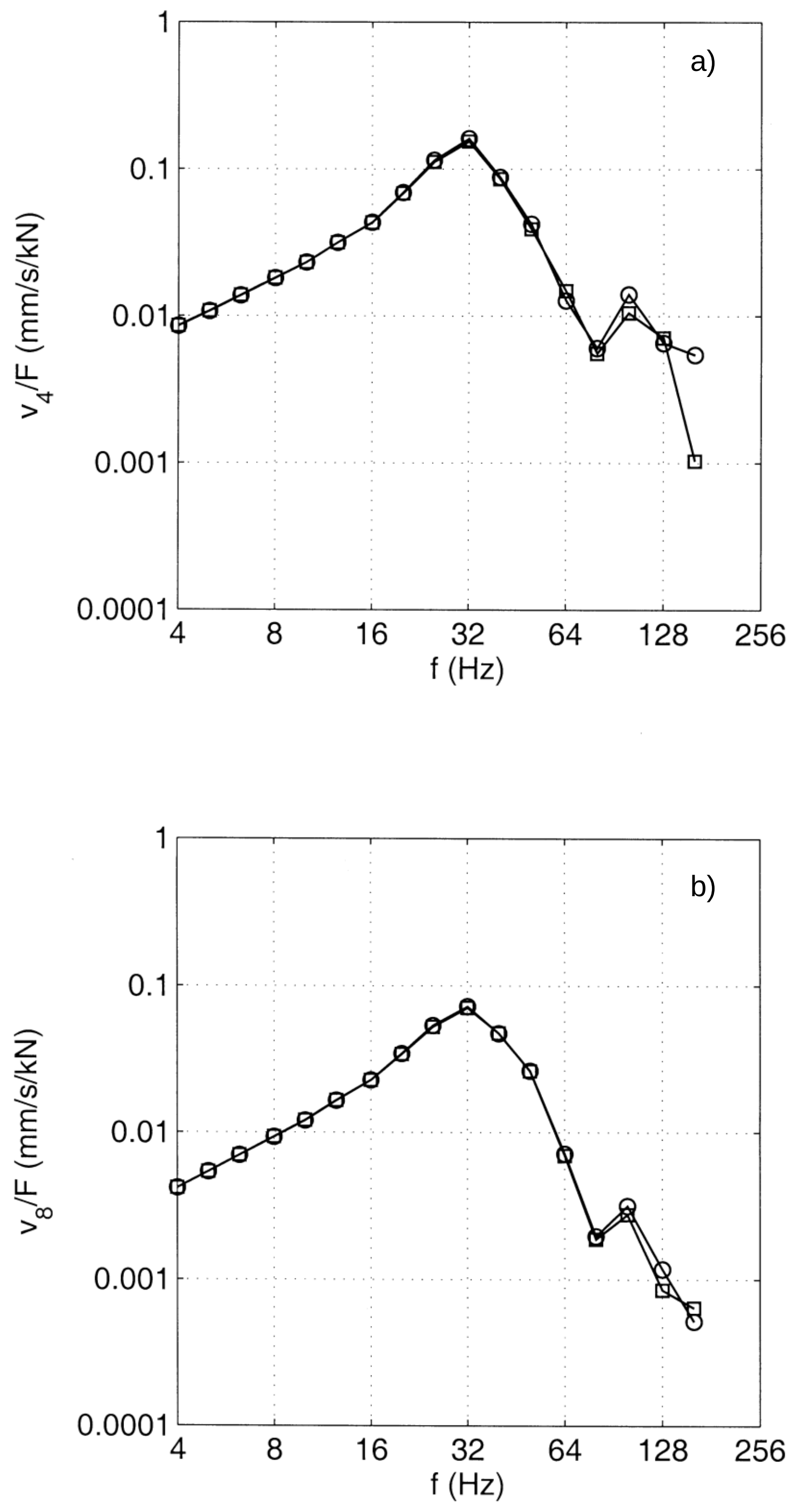


Figure 15-11: Slab tracks with different sleeper distances *d* = □ 0.6, ○ 0.65 m, mobilities of the soil at a) 4, and b) 8 m distance from the track, including vehicle-track interaction

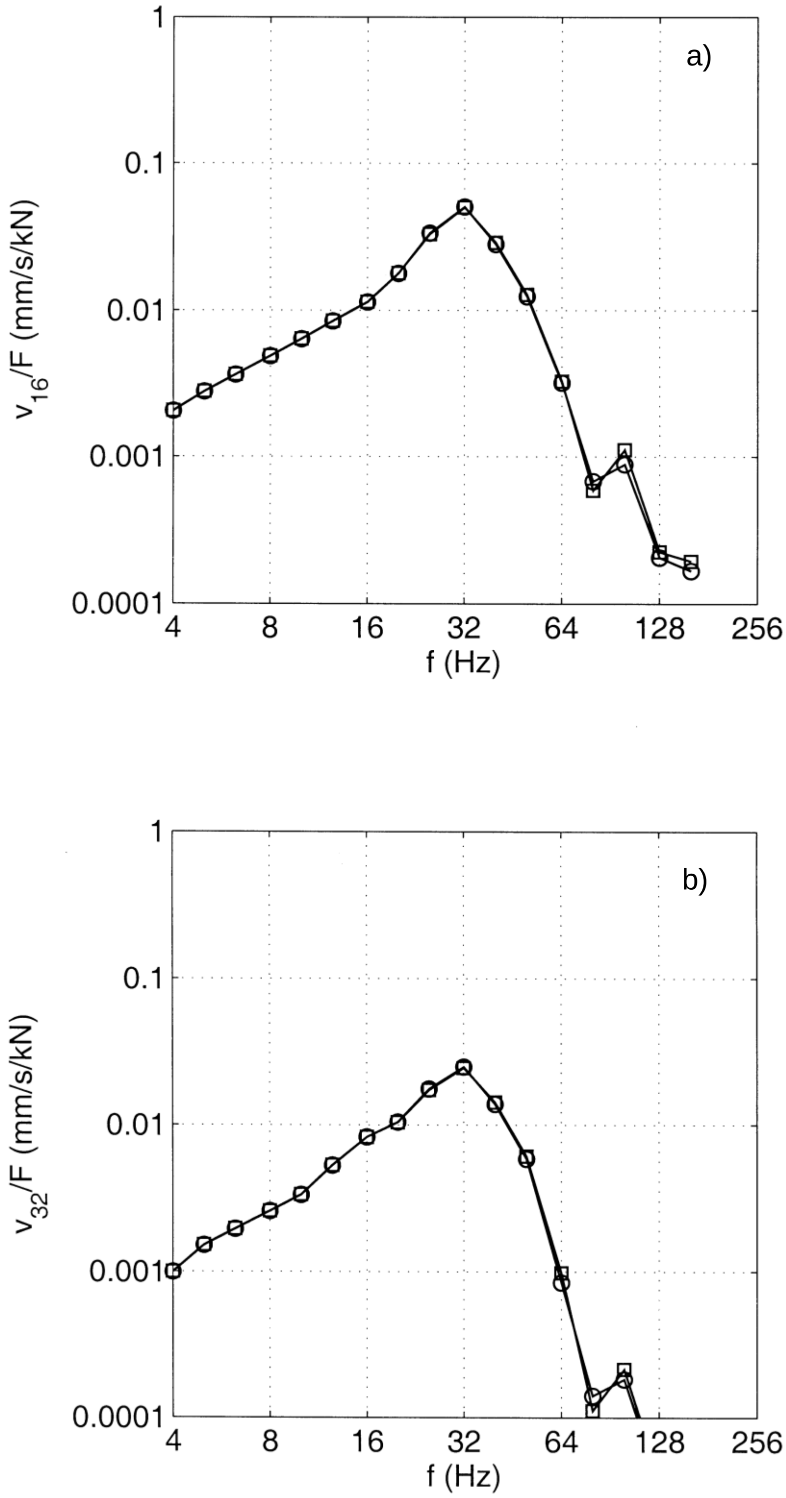
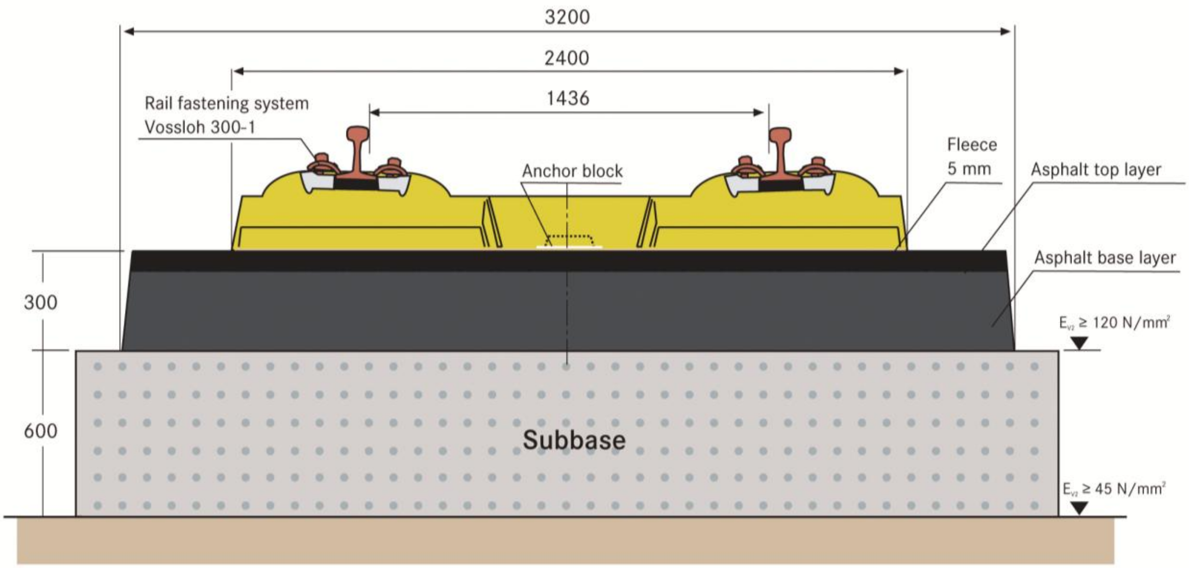


Figure 15-12: Slab tracks with different sleeper distances *d* = □ 0.6, ○ 0.65 m, mobilities of the soil at a) 16, and b) 32 m distance from the track, including vehicle-track interaction

16. APPENDIX F – THE GETRAC SYSTEM WITHOUT AND WITH UNDER SLEEPER PADS

a)



b)

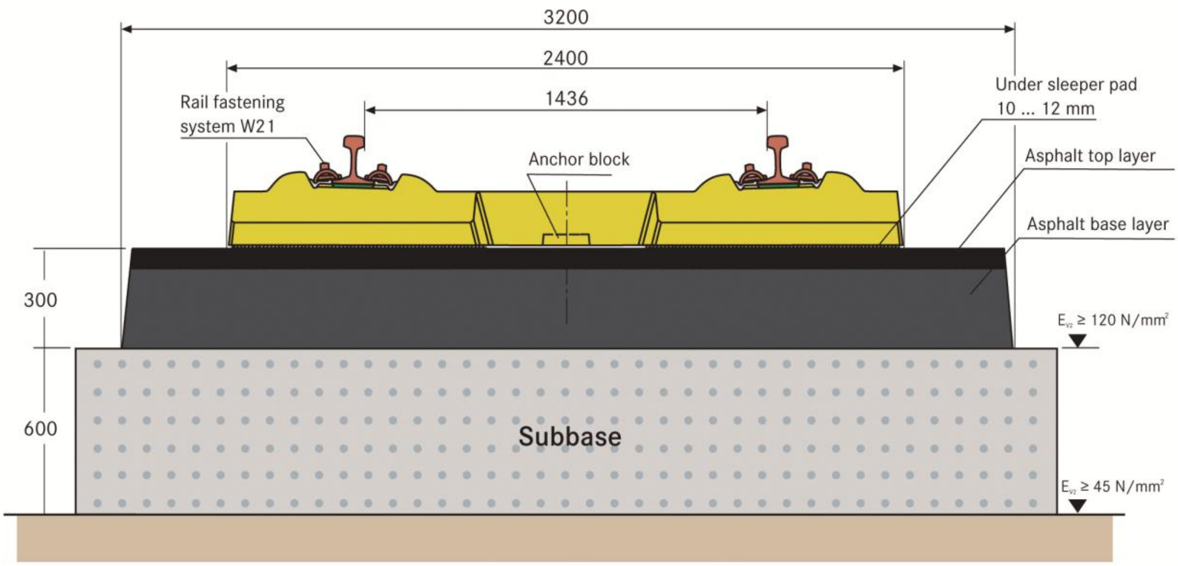


Figure 16-1: The GETRAC System a) without and b) with under sleeper pads