Vibration isolation in soil by thin injected foam barriers

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ABSTRACT: The isolation of excessive noise and vibration plays an important role for the usability of buildings close to vibration sources, such as railway lines. By installing noise protection walls along the vibration source, the noise, which is mainly travelling through air, can be reduced remarkably. Following this principle the vibrations, which are running through the ground, can be reduced by thin vertical foam barriers, injected into the soil. These barriers could be a promising alternative to conventional vibration isolation methods, e.g. spring elements or elastomer mats. The advantages of these thin foam barriers are notable savings in material and time, because of the simpler installation procedure. However, the effectivity of those barriers has still to be proven by in situ measurements. Until now, there is no tool to predict its impact on vibrations.

This paper will present first results from a field test that was carried out in a gravel pit, using a hydraulic shaker unit as vibration source. By measuring and comparing the soil velocities before and after installation of the foam barrier, the effectivity of the isolation measure has been evaluated. The promising results indicate a significant reduction of the soil velocities and are used for the calibration of a numerical model.

Keywords: vibration isolation, geofoam barriers, polyurethan, soil dynamics

1 INTRODUCTION

The growing demand for public and commercial transportation in the past years has led to a significant expansion of the railway network in Germany. Problems caused by frequently used railway tracks are increased emissions, such as noise and vibrations, produced by passing trains. Since many of these tracks are located within urban areas, the protection of the residents plays a significant role in the planning process. If not attenuated, vibrations affect the quality of living in the area of railway tracks. In extreme cases vibrations may even lead to the loss of the usability of a building.

Several measures have been used in the past to reduce vibrations. Usually these measures are distinguished by the location of their installation in the area of emission, transmission or immission (see Figure 1), where the area of transmission defines the area between the vibration source and the object to be protected.

Conventionally, in the area of emission, mass-spring-damper systems that act as elastic foundations, decoupling the tracks from the ground, are installed underneath the railway tracks. The installation of such a system should be planned before construction. If applied on existing railway tracks, the installation constraints the daily operation of the railway. In the area of immission, the decoupling of the foundation from the ground by an elastic material is a common attenuation method. However, the installation of the elastic material between soil and foundation has to be carried out during the construction of the building, a subsequent installation is usually not feasible.

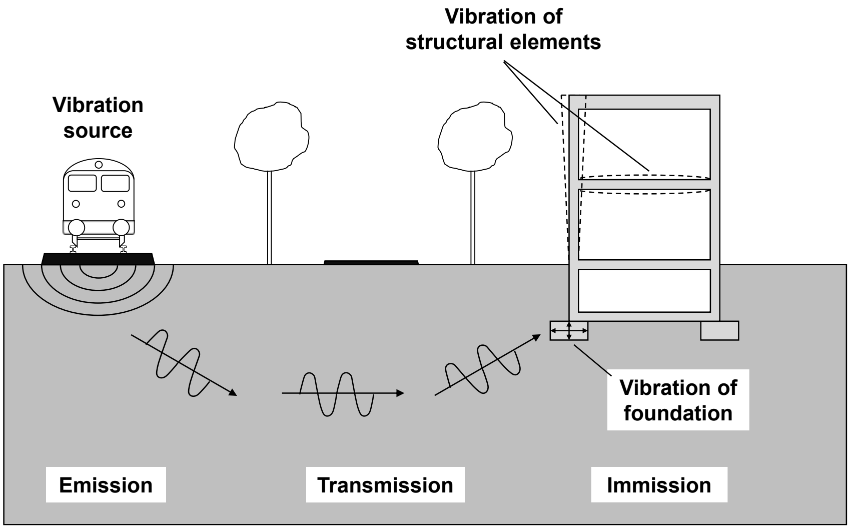

Figure 1. Area of emission, transmission and immission

An alternative to the measures mentioned above are underground barriers in the transmission area. Existing techniques usually comprise a vertical trench that is filled with a material that clearly differs in density compared to soil, such as concrete or gas mats. The installation of a vertical barrier in the soil made of polyurethan foam (PU-foam) represents a new and innovative vibration isolation measure. It can be used on existing and yet-to-be-planned vibration sources, without constraining the use of neither the vibration source nor the object to be protected. The present paper gives special attention to the evaluation of the effectivity of these geofoam barriers.

2 STATE OF THE ART

Haupt (1978) already carried out experimental and numerical studies on open and in-filled trenches as vibration isolation measure in the transmission area. The objective of the study was the investigation of the influence of different fillings on the isolation effectivity. He showed that the difference in density and stiffness between soil and filling is the decisive parameter for the success of trenches as vibration isolation method. This difference is commonly expressed by the impedance ratio IR:

$$IR = \frac{\rho_M \cdot c_M}{\rho_S \cdot c_S} \qquad (1)$$

where ρ_M and ρ_S represent the density in kg/m³ of the trench material and the soil, respectively, and c_M and c_S denote the shear wave velocity in m/s of the trench material and the soil, respectively.

The impedance ratio IR affects the degree of reflection and transmission of wave energy and amplitude at a material boundary. As expected, Haupt (1978) achieved best results by open trenches. The effectivity of vibration isolation measures in the transmission zone is usually expressed by the amplitude reduction factor AR. This factor is calculated by comparing the velocities before (v_0) and after (v_+) the installation of the isolation barrier over a defined area A behind the trench or barrier. Hence, a low AR means a high vibration reduction and vice versa:

$$AR = \int_A \frac{v_+}{v_0} dA \qquad (2)$$

Sadegh-Azar (2010) investigated the correlation of amplitude reduction factor AR and impedance ratio IR by carrying out numerous numerical calculations. In accordance with the findings of Haupt (1978), the best results amplitude reduction factors AR were observed for very high or low values of the impedance ratio IR. He showed that a low IR (i.e. << 1.0) is achieved by using open trenches or a filling with low density. For high values of IR (i.e. >> 1.0), a satisfying attenuation is achieved only for very deep and wide trenches. Those results were confirmed in many experimental and numerical studies (e.g. Woods 1968, Adam & von Estorff 2005).

The effectivity of a vertical barrier is also strongly influenced by its geometry, especially by its depth (e.g. Woods 1968, Haupt 1978). This influence on the amplitude reduction can be explained by the characteristics of the Rayleigh wave. Figure 2 shows the distribution of the vertical soil velocity versus depth for the Rayleigh wave, which transmits most of the wave energy in soil and is a surface wave. With increasing depth the vertical soil velocity decreases rapidly. 70 % of the total energy of the wave is transmitted within a depth t equal to the wave length λ_r (Richart et al 1970). Thus, the best results for a vibration reduction are achieved for values of t being higher or equal to at least $0.5 \cdot \lambda_r$. That implies that very deep barriers are necessary for low frequencies, because low frequencies correspond to long wave lengths. As a consequence, barriers should always be realised as deep as possible.

Although open trenches would provide a very effective vibration isolation, in many soils open trenches would not stay open but collapse. Gas mats represent a filling with low density and can be placed in a previously excavated trench. The mats turn out to be very effective regarding vibration reduction, but susceptible to failure and difficult to install. Regarding fillings with a high IR, massive concrete walls proved to be very costly and impossible to install especially in urban spaces because of crossing pipes and wires. Both systems have not been established until today.

Alzawi & Hesham El Naggar (2011) were the first to use geofoam as a filling for isolation barriers. The advantages of geofoam are the very low density combined with a stiffness that ensures the stability of the trench. In field tests with a 25 cm wide trench remarkable vibration reduction was obtained.

The research project currently carried out at the institute of Geotechnical Engineering at RWTH Aachen University aims at improving the usability of geofoam as vibration isolation material. There are three main objectives of the project: first, the improvement of the installation method, second, to prove its effectivity by conducting field tests, and third, the development of a numerical prediction tool for future projects. The research project is carried out in cooperation with the German company URETEK Deutschland GmbH. URETEK are experts in the use of geofoam in geotechnical applications, such as ground improvement or heaving of unwanted settlements. Beyond that, the geofoam used in their applications features all characteristics of an excellent isolation material, i.e. a low density to reduce vibrations along with a relatively high stiffness to ensure the support of the barrier. Besides, its long term environmental and groundwater compatibility has already been analysed and approved by the authorities.

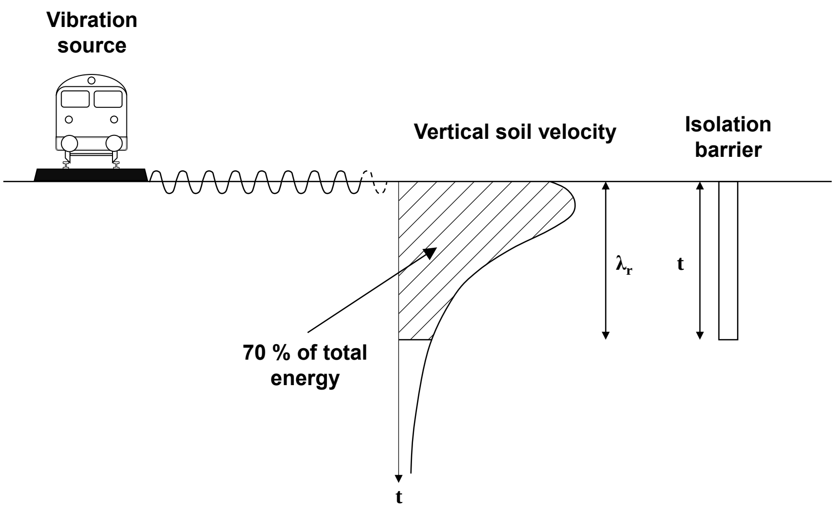

Figure 2. Schematic distribution of vertical soil velocity and wave energy for Rayleigh waves

3 FIELD TESTS

Field tests were carried out in a gravel pit near Aachen, Germany, where the soil consists of a homogenous mixture of sandy gravel. Using a hydraulic shaker, the soil was excited by a harmonic load with various frequencies. Measurements of the soil velocities at different points were performed for two situations, before (reference measurement) and after (reduction measurement) installation of the isolation barrier. Finally, the amplitude reduction was evaluated by comparing the velocities of each point.

3.1 *Ground conditions*

In soil dynamics, the soil velocities and soil damping are the most significant parameters for the description of the dynamic soil behaviour. Here, the velocities are determined by a Multichannel Analysis of Surface Waves (MASW). This method allows the determination of shear wave velocities versus depth. When soil is subjected to very small deformations, its behaviour can be considered as linear elastic (Richart et al. 1970). The relation between soil velocity v_s, shear modulus G and soil density ρ can then be described by the following formula:

$$v_s = \sqrt{\frac{G}{\rho}} . \qquad (3)$$

The Young's modulus can be derived from Equation (3) by using the relations between shear modulus, Young's modulus and Poisson's ratio. A Poisson's ratio of $\nu = 0.3$ for sandy gravel was assumed (Bowles 1996).

The medium soil density in-situ was determined to 1.8 g/cm³. Hence, the Young's modulus vs. depth was calculated and is plotted in Figure 2. The figure shows the Young's modulus resulting from the MASW and its linearization and extrapolation, which has been used for the finite element (FE) calculations of chapter 4.

Soil damping in terms of Rayleigh damping cannot be determined directly from the results of in-situ tests. The damping ratio ξ and the actual Rayleigh damping parameters α and β were evaluated by comparison of the soil velocities of the field test with the calculated velocities from the numerical model (see chapter 4).

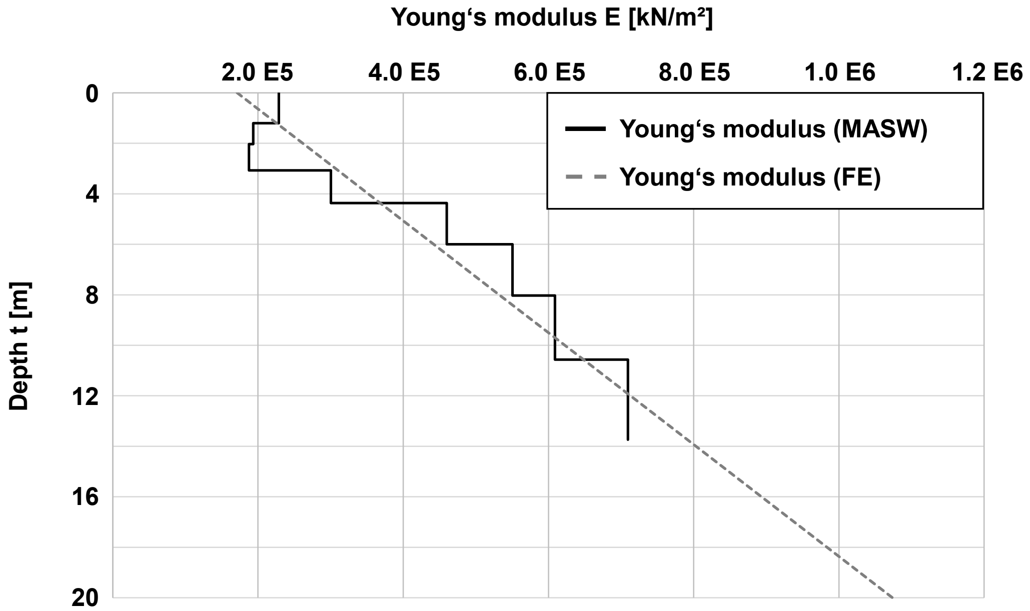

Figure 3. Young's modulus vs. Depth

3.2 *Vibration source*

The excitation of the ground was induced by a hydraulic shaker. This device, as shown in the lower right corner of Figure 4, was founded on four steel plates. On top of the foundation a hydraulic aggregate and an oscillation unit were installed. During one sweep, the shaker passed the range from 10 Hz to 110 Hz, accelerating in steps of 0.1 Hz. After a short warm-up phase it took approximately six minutes to run a whole sweep. The dynamic force of the shaker oscillated with a constant amplitude of 5 kN. Since the static load of the shaker was about 4.8 kN, the dynamic force P_{dyn} acting on the ground was varied between -0.2 kN and 9.8 kN. In Figure 4, the increase of the frequency versus time, as well as the constant amplitude range of the dynamic force versus time during one sweep, are plotted. In this case, after about 100 seconds the frequency of approximately 35 Hz was reached, which turned out to be the eigenfrequency of the soil-shaker system. In this frequency range the shaker had to adapt to the resulting resonance in the system, which explains the small deviation of the dynamic force.

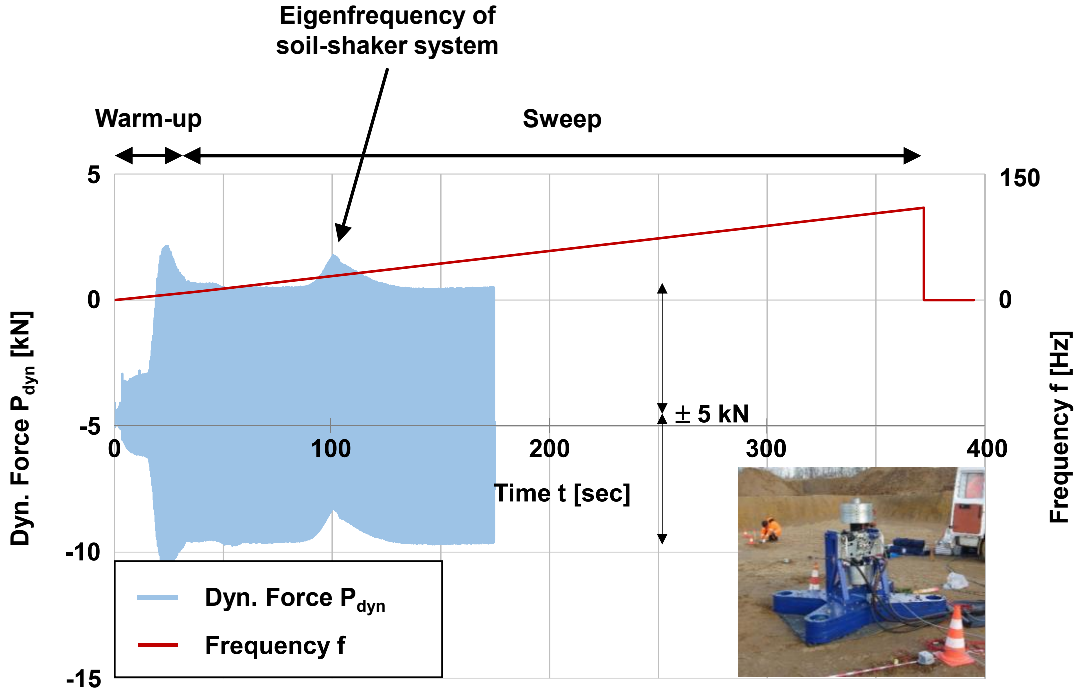

Figure 4. Performance data of hydraulic shaker: Dynamic Force and Frequency vs. Time

3.3 *Instrumentation and test setup*

The instrumentation consisted of four velocity pick-ups, four connector boxes, a processor box where the analog signal was digitalized, and a laptop. For recording and processing of the data the software MESSI (2015), written and owned by the Institute of Structural Analysis and Dynamics of RWTH Aachen University, was used. Special attention was paid to the connection between velocity pick-ups and ground, because any loose connection between pick-up, earth spike and ground would have produced additional vibrations and therefore would have falsified the results (DIN 45669-2:2005-06). Therefore the connection was realised by earth spikes as shown in Figure 5.

In Figure 5 the dimensions and the test setup as well as a picture of the isolation barrier are displayed. The shaker was placed at two different positions. During the first setup the shaker was positioned, related to the barrier, in the far field, which was 12 m in front of the barrier position (not shown in Figure 5). For the examination of the near field in the second setup, the shaker was sited just 2 m in front of the barrier (position A0.2). Since only four velocity pick-ups could be used at once, two series of measurements were necessary for both setups.

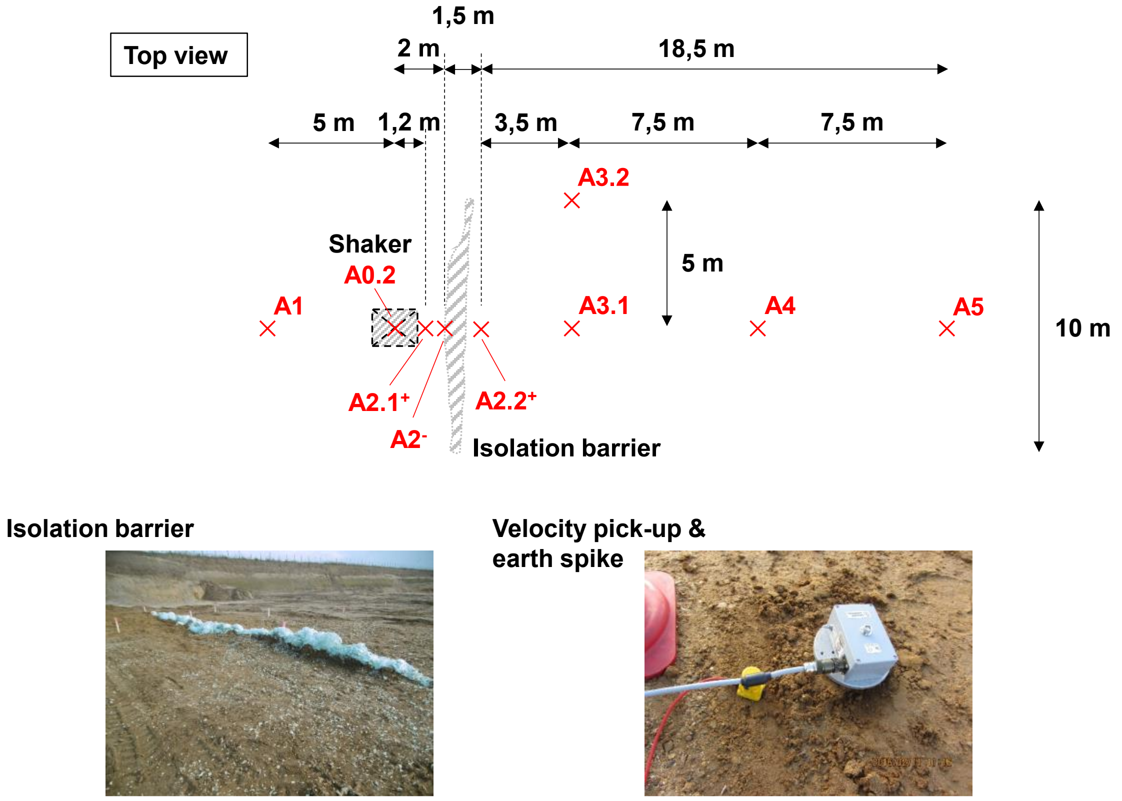

Figure 5. Top view of test setup and impressions from the field test

The reference measurements (or zero measurements) comprised measurements at the points A0.1$^-$ or A0.2$^-$, A1$^-$, A2$^-$, A3.1$^-$, A3.2$^-$, A4$^-$, and A5$^-$. The reduction measurements included measurements at the points A0.1$^+$ or A0.2$^+$, A1$^+$, A2.1$^+$, A2.2$^+$, A3.1$^+$, A3.2$^+$, and A4$^+$. Reference measurements will always be indicated by a superscript - and reduction measurements by a superscript +, respectively. Each measurement was performed twice to ensure reproducibility and to avoid mistakes. In this paper, due to the limited space, only the results for the near field are presented.

3.4 *Isolation barrier*

After carrying out the reference measurement, the isolation barrier was installed. The barrier was 15 - 20 cm wide, 1.60 – 3 m deep and 10 m long (see Figure 5). To obtain the material parameters of the used geofoam, laboratory tests were carried out. The results showed a medium density of $\rho = 0.03$ g/cm³, a medium stiffness of $E = 1300$ kN/m² and a Poisson’s ratio close to zero. A detailed description of the installation process of the barrier will be published elsewhere soon.

3.5 *Results*

The recorded signal of the soil velocities was stored in the time domain. Since the amplitude reduction strongly depends on the frequency of the signal, the data have to be transformed into the frequency domain. This was achieved by applying the Discrete Fourier Transformation (DFT). In Figure 6, the soil velocities of the reference measurements (point A2$^-$, located exactly at the position of the barrier to be installed) and the reduction measurements (point A2.2$^+$, located just behind the installed barrier) are plotted in the frequency domain. This representation allows a quick but substantiated evaluation of the success of the vibration isolation measure for all frequencies at one position. The partially strong fluctuation of the soil velocities resulted from the control technique of the shaker, which is constantly adjusting its force during a sweep. As a consequence, the force, as well as the soil velocities, slightly vary for each frequency step. With increasing distance from the hydraulic shaker, this effect reduces.

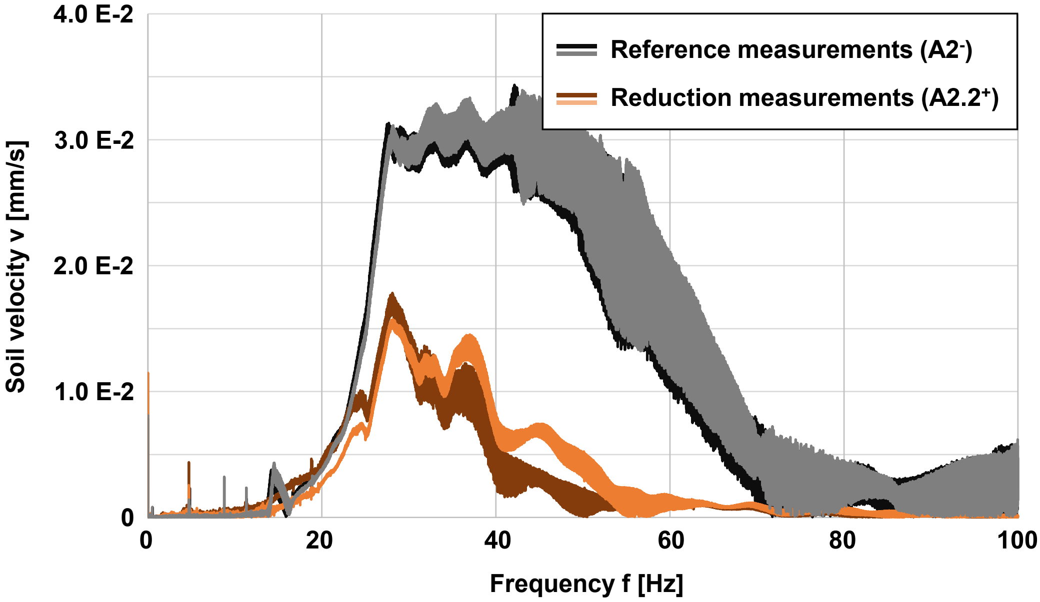

Figure 6. Soil velocity of points A2- & A2.2+ in frequency domain

It becomes apparent that for frequencies f > 30 Hz a high reduction is achieved. For example, the soil velocity for the frequency f = 50 Hz is reduced from approx. 2.5e-2 mm/s down to 0.2 to 0.5 mm/s. This corresponds to a reduction of about 80 to 90 %. Generally it can be seen that the lower the frequency of the signal gets the worse the reduction of the soil velocities is. This can be explained by the shallow depth of the barrier in the field test, which was just about 2 m on average. The general influence of the barrier depth on the amplitude reduction is described in chapter 2 of this paper.

The influence of the installation of the isolation barrier on the soil velocities is shown for point A2.2+ in Figure 6. All other points were analysed respectively. In the following, all measured soil velocities are normalized with respect to the velocity at the position of the shaker. In Figure 7, the normalized soil velocity is plotted versus the distance from the vibration source (position A0.2, compare Figure 5) for the frequency f = 50 Hz

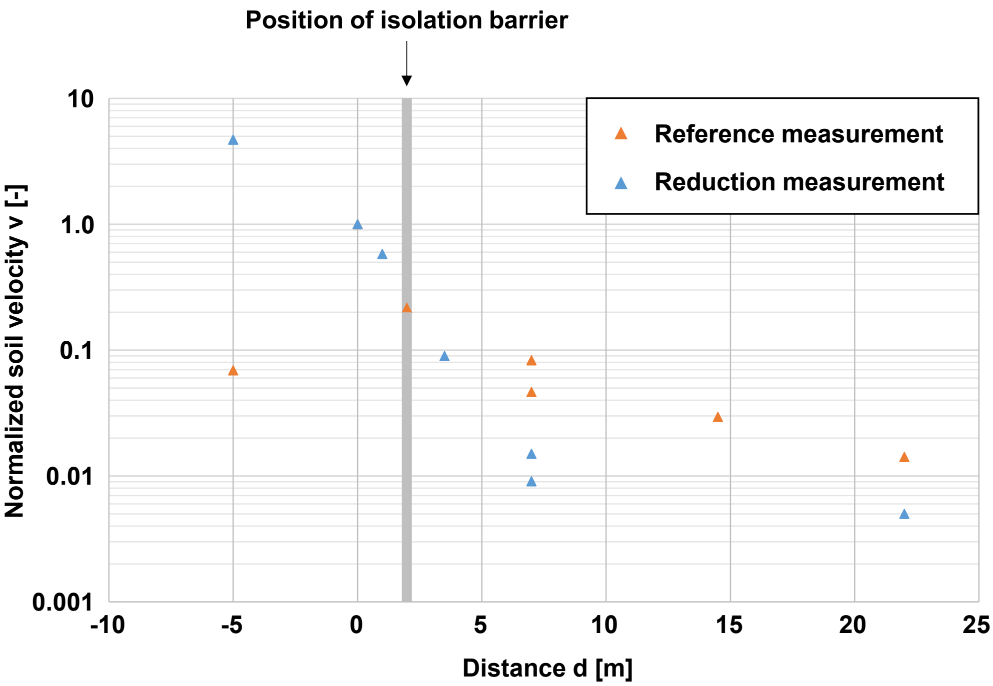

Figure 7. Normalized soil velocity vs. Distance (f = 50 Hz)

By comparing the results of the reference and the reduction measurement, the influence of the isolation barrier can clearly be seen. Before installation of the isolation barrier (reference measurement), the soil velocities on average decrease steadily over distance, because of geometric and material damping in the soil. After installation of the barrier (reduction measurement), the effect of wave reflection at material boundaries can be observed in front of and behind the barrier. While the soil velocities in front of the barrier are considerably higher after installation of the barrier, there is a steep decrease of the soil velocities behind the barrier. For example, at the distance d = -5 m (point A1, in front of the barrier) the normalized soil velocity increases from 0.08 to 2.0. However, at the distance d = 7 m (points A3.1 and A3.2, behind the barrier) the normalized soil velocities decrease from 0.09 to 0.01 and from 0.05 to 0.015, respectively. Although Figure 7 shows only the results for f = 50 Hz, the results for all frequencies f > 30 Hz look similar.

As described before, the amplitude reduction is usually expressed in terms of the amplitude reduction factor AR. The AR is calculated for each point and for each frequency by comparing the soil velocities before (v_0) and after (v_+) installation of the barrier. The AR is calculated as the arithmetic average of all measured points behind the barrier. Hence, for a frequency of 50 Hz the AR_{50} is calculated by the following formula:

$$AR_{50} = \frac{\sum_{i}^{n_i} AR_{50,i}}{n_i} . \qquad (4)$$

In Figure 8, the AR is plotted versus different frequencies, confirming the first visual results of Figure 6. That is, the higher the frequency the higher the AR and therefore the better the reduction effect. It can be seen that the effectivity of the reduction is increasing rapidly with higher frequencies. A fitted curve was added to the plot to illustrate the general relation between frequency and amplitude reduction factor AR.

Summing up, the results of the field test showed that an isolation barrier made of geofoam is very effective. For frequencies higher than 30 Hz the amplitudes have been decreased by ~50 - 60 %. The most important parameter for the success of the isolation measure turned out to be the depth of the barrier. In the field test, the depth varied between 1.60 m and 3 m, with a medium depth of ~2 m. Therefore for low frequencies f < 30 Hz no reduction effect was observed. On the contrary, even an increase of soil velocities was noted. For practical applications the barrier should always be at least 3 m deep. For a deeper barrier, it is expected that the curve from Figure 8 shifts towards lower frequencies and appropriate amplitude reduction factors AR < 1 are achieved even for frequencies lower than 30 Hz.

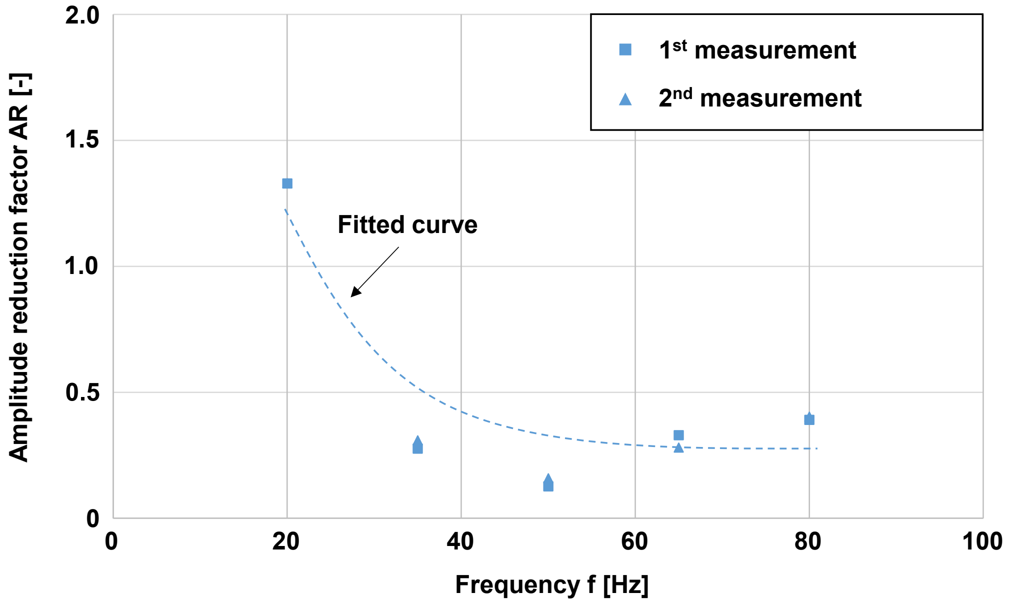

Figure 8. AR vs. Frequency

4 NUMERICAL STUDIES

A numerical 3D-model is set up to study the influence of thin and vertical PU-foam barriers on vibrations in soil. The overall goal is the development of a prediction tool for vibration attenuation, which can be used to estimate the effect of PU-foam barriers in practical applications. For this purpose, the dynamic module of the finite element software Plaxis is utilised. In this paper, first results of the calibration of the model with the field test are presented.

4.1 *Numerical model*

The model dimensions are 50 m × 30 m × 20 m (length × width × height) and viscous boundaries are used to avoid reflection of waves at the model boundaries. As stated before, for small displacements the material behaviour of the soil and the foam is considered as linear elastic. The hydraulic shaker is modelled by a stiff steel plate with a dead weight of 4.8 kN. For the simulation of the vibration a vertical and harmonic dynamic load with the amplitude 5 kN and varying frequencies is applied to the steel plate. In accordance with the field tests, the steel plate is placed at two different positions.

For the calibration of the model, both, the reference and the reduction measurement, are simulated. At the beginning of each simulation, the initial stresses are calculated. The excavation of the trench is simulated afterwards and is followed immediately by the activation of the geofoam material. Then, the static load is applied to the soil. After activation of the dynamic load the calculation lasts until the maximum amplitudes of the soil velocities are constant for each point. The model then reaches the ‘steady state’. In case of the reference measurement, the excavation of the trench and the activation of the geofoam material are omitted. The evaluation of the soil is performed during the ‘steady state’ at the points corresponding to the equivalent points of the field test.

4.2 *Material properties*

The dynamic module used in Plaxis was verified by extensive numerical calculations, which are not shown here. After verification, the 3D model is calibrated, using the results from the field test. For the calibration of the soil model, its damping parameters are adjusted. The stiffness parameters are chosen according to the MASW results shown in Figure 2 and the damping ratio ξ is varied between 3 % and 15 %. In Figure 9, the normalized soil velocities are displayed versus distance for the examples of f = 50 Hz for the reference measurement. The damping ratio in this case is chosen to ξ_{50} = 5 %.

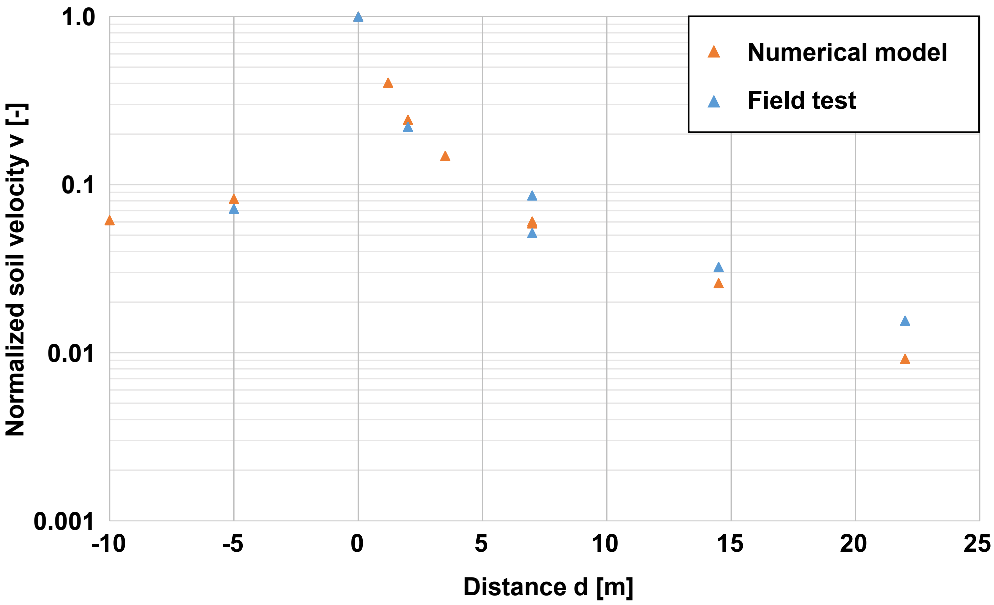

Figure 9. Calibration of soil parameters: Normalized soil velocities vs. Distance (f = 50 Hz)

The comparison of the numerical model and the field test, in Figure 9 displayed for 50 Hz, shows a good agreement between the results. For all other frequencies, the damping ratio is adjusted accordingly, leading to at least reasonable agreements between field test and numerical calculations. As expected, the damping ratio is higher for higher frequencies. The determination of the unit weight and the Poisson's ratio of the soil is described in chapter 3.1. The material parameters of the foam correspond to the results from laboratory tests (see chapter 3.4). Table 1 gives an overview of the material parameters used for the numerical calculations.

Table 1. Material parameters for soil and foam

	Parameter	Value
Soil	Unit weight γ	18 kN/m³
	Young's modulus E_{oed}*	171,300 kN/m² (at z = 0 m) 1,074,100 kN/m² (at z = 20 m)
	Poisson's ratio ν	0.3
	Damping ratio ξ**	3 % (for f =20 Hz) 5 % (for f =50 Hz) 10 % (for f = 80 Hz)
Geofoam	Unit weight γ	0.3 kN/m³
	Young's modulus E	1,300 kN/m²
	Poisson's ratio ν	~0

*linear growth with depth
**frequency dependent

4.3 *Results*

In the previous chapter, it is shown that the wave propagation in soil is simulated correctly. If used as a prediction tool, the numerical model must not only simulate the wave propagation in the free field but also when interfered by underground barriers. Figure 10 shows the results for the simulation of the reduction measurements, as normalized soil velocities versus distance for 50 Hz.

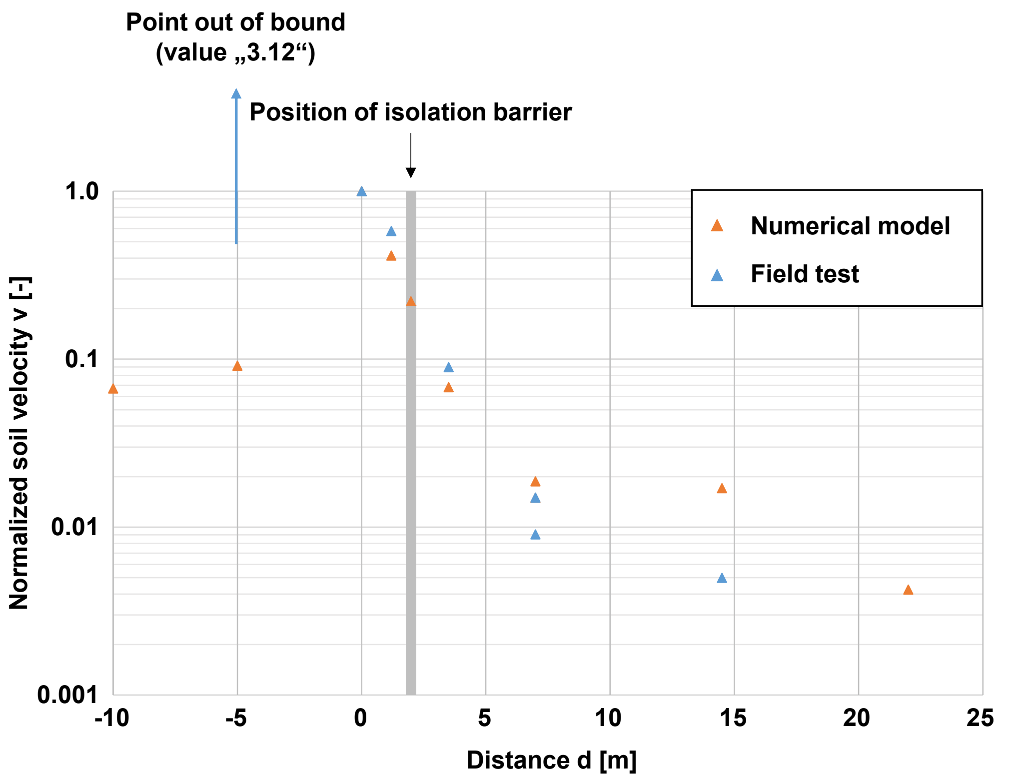

Figure 10. Calibration of soil parameters: Normalized soil velocities vs. Distance (f = 50 Hz)

The reduction effect observed in the field test is qualitatively reproduced by the numerical model. The difference between numerical model and field test can be explained by the simplifications made in the numerical model. The soil is considered isotropic and homogenous, i.e. all material properties are independent from their location in the model. Both, the wave propagation and the geometry of the contact area between the soil and the geofoam, are idealized. As a consequence, no effects due to local inhomogeneities are modeled. In the field test, local inhomogeneities in the soil can cause peak values that do not fit with the assumed linear elastic soil behavior. Besides, the actual shape of the barrier is not known exactly and the material properties of the geofoam vary slightly over the cross section. Having this in mind, the numerical model can be considered as an appropriate tool for the prediction of soil velocities for both the reference and the reduction measurements.

Finally, in accordance to the evaluation of the field test, the amplitude reduction factor AR can be determined from the numerical calculations for each frequency. In contrast to the field test, the calculation of the AR in the numerical calculations is based on more than four points, so that the influence of the variance of the values can be reduced considerably. The resulting AR are compared to the measured AR as shown in Figure 8 and plotted in Figure 11. It can be seen, that the numerical calculations reproduce the measured values, represented by the fitted curve, well. Hence, the numerical model can simulate the propagation of soil velocities in the ground for both situations, with and without isolation barrier.

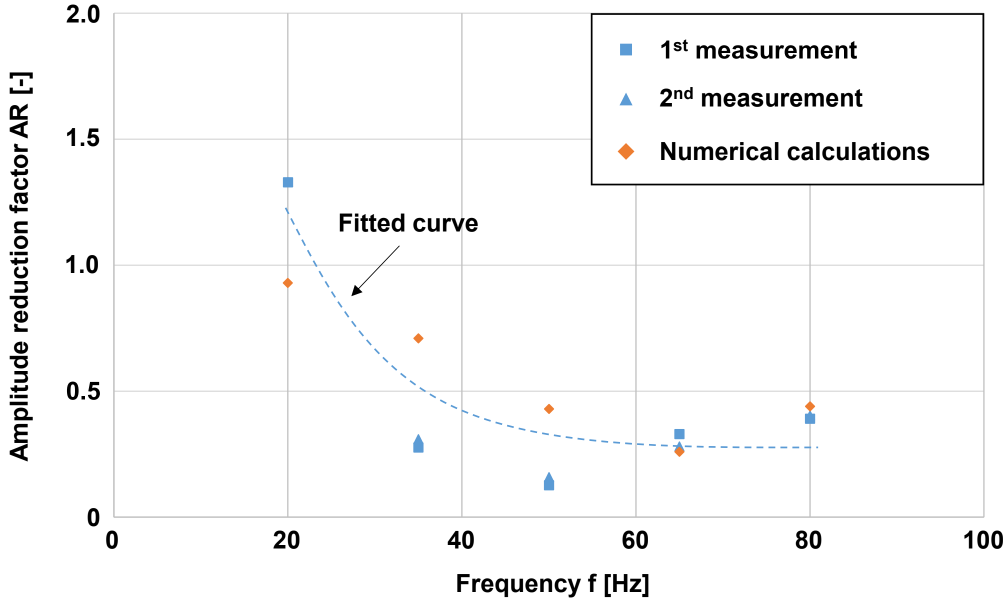

Figure 11. AR vs. Frequency (field test and numerical calculations)

5 CONCLUSION

Field tests were carried out with a hydraulic shaker to evaluate the reduction effect of a vertical foam barrier injected into the soil. First results from this field test were presented. Additionally, a numerical model was set up and calibrated using the results from the field test.

The following conclusions can be drawn:

- The soil velocities are reduced significantly for frequencies higher than 30 Hz, the achieved amplitude reduction factor AR is about 50 % to 60 %.
- The depth of the barrier is the most influential parameter for its effectivity. Although good results are achieved even with a medium depth of about 2 m, a greater depth is recommended.
- The numerical model reproduces the wave propagation well.
- For the situation after installation of the barrier, the numerical model also shows reasonable results. The prediction of the amplitude reduction factor AR fits well with the measured values from the field test.
- Differences between numerical simulations and field tests are due to local inhomogeneities in-situ that can hardly be considered in a numerical model.

6 ACKNOWLEDGMENTS

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7 REFERENCES

Adam M. and von Estorff O. (2005) Reduction of train-induced building vibrations by using open and filled trenches. *Computers and structures* **83**, No. 1, pp.11-24.

Alzawi A. and Hesham El Naggar M. (2011) Full scale experimental study on vibration scattering using open and in-filled (GeoFoam) wave barriers. *Soil Dynamics and Earthquake Engineering* **31**, pp. 306-317.

Bowles J.E. (1996) *Foundation Analysis and Design (5th Edition).* McGraw-Hill Book Company.

DIN 45669-2:2005-06, Messung von Schwingungsimmissionen – Teil 2: Messverfahren (in German).

Haupt W. (1978) Verhalten von Oberflächenwellen im inhomogenen Halbraum mit besonderer Berücksichtigung der Wellenabschirmung. *Veröffentlichungen des Institutes für Bodenmechanik und Felsmechanik der Universität Fridericiana in Karlsruhe, Germany* Heft 74 (in German).

MESSI (2015) – Auswerteprogramm für Messtechnik in Lehre und Forschung. Unpublished Manual (in German).

Richart F.E., Hall J.R. and Woods R.D. (1970) *Vibrations of soils and foundations.* Prentice-Hall.

Sadegh-Azar P. (2010) Erschütterungsreduktion durch aufgeschäumte Isolierkörper im Boden. *Schriftenreihe Geotechnik im Bauwesen, RWTH Aachen, Germany* Heft 2 (in German).

Woods R.D. (1968) Screening of surface waves in soil. *Journal of Soil Mechanics and Foundation Engineering (ASCE)* **94**, No. SM4, pp. 951-979.