The dynamic behavior of railway tracks with under sleeper pads, finite-element boundary-element model calculations, laboratory tests and field measurements

Lutz Auersch, Samir Said, Esther Knothe, Werner Rücker
1BAM Federal Institute of Material Research and Testing, D 12200 Berlin, Germany
email: lutz.auersch-saworski@bam.de, samir.said@bam.de

ABSTRACT: A variety of isolation measures exist to reduce the vibration in the neighbourhood of railway lines. They can be roughly classified as elastic or stiffening systems. There are the following elastic elements, rail pads or resilient fixation systems between rail and sleeper, under sleeper pads or sleeper shoes under the sleepers, and ballast mats under the ballast. Stiffening systems (plates) are used as slab tracks, floating slab tracks, or mass-spring systems. In the EU project “Railway induced vibration abatement solutions (RIVAS)”, elastic under sleeper pads have been investigated. The dynamic behaviour of the track and the surrounding soil has been calculated by the combined finite-element boundary-element method in a systematic parameter study. It has been shown that the mitigation effect can be improved by soft under sleeper pads or by heavy sleepers. Consequently, such track elements (soft under sleeper pads and heavy sleepers) have been thoroughly investigated in laboratory tests to establish the static and dynamic parameters as well as their serviceability. Finally, field tests at and near railway tracks with and without under sleeper pads have been performed. To determine the reduction effect of the isolated track, the ground vibrations excited by trains or artificial sources have been measured. The soil properties at the different sites have also been measured so that the comparison of the isolated and un-isolated track can take into account possible differences of the soil parameters. The contribution shows how the different (numerical, laboratory and field) methods and results can be combined to achieve an improved mitigation solution with soft under sleeper pads and heavy sleepers for ballasted and slab tracks.

KEY WORDS: railway track, track-soil interaction, mitigation, under sleeper pads, laboratory tests, field tests, ground vibration.

1 INTRODUCTION

From 2011 to 2013, the BAM Federal Institute of Material Research and Testing worked for the European research project RIVAS - Railway Induced Vibration Abatement Solutions, which is carried out by 27 partners from nine European countries within the 7th European Framework Programme. RIVAS aims at reducing the environmental impact of ground-borne vibration from rail traffic by measures at the vehicle, the track and the soil. BAM’s main contribution to this project deals with the mitigation solutions for the track.

The different tasks of the BAM will be described in the following sections, the calculation of the vehicle-track-soil system by the combined finite-element boundary-element method in Section 2, the laboratory testing of track elements such as soft under sleeper pads and heavy sleepers (Fig. 1) in Section 3, and finally in Section 4, the field tests near railway tracks for the evaluation of soil parameters and reduction effects.

2 NUMERICAL STUDIES

2.1 Finite-element boundary-element method

The track-soil systems are calculated by the combined finite-element boundary-element method [1,2,3]. The track including the rails, rail pads, sleepers, under sleeper pads, and ballast has been modeled by the finite element method (Fig. 2) whereas the homogeneous or layered soil has been modeled 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 [3,4]. All calculations (Green’s functions, boundary matrix and finite element matrices) are performed in the frequency domain. Special additional methods (within the FEBEM) have been developed for infinite tracks on ballast mats [5] and are also applied to this study. Infinite slab tracks and floating slab tracks can also be analysed by wavenumber domain methods [6], but in RIVAS FEBEM models of slab tracks have been used.

The track is excited by a dynamic axle load (a pair of vertical forces) which acts on the rails above the central sleeper. In a second step, the FEBEM track-soil model is combined with a vehicle model [7] which is a single wheelset throughout this contribution. The ground vibration at some distances of the track are calculated and compared for the isolated and un-isolated track.
2.2 Parameters

The only parameter of the vehicle is the wheelset mass $m_w = 1500$ kg.

The reference ballasted track has the following parameters, bending stiffness of the rails (UIC60) $EI = 2 \times 2.1 \times 10^{11} \times 3.0 \times 10^{-3}$ Nm², mass per length of the rails $m'_r = 2 \times 60$ kg/m, distance of the sleepers $d = 0.6$ m, stiffness of the rail pads $k_p = 300 \times 10^6$ N/m, modulus of elasticity of the sleepers $E_s = 3 \times 10^{10}$ N/m², mass density of the sleepers $\rho_s = 2.5 \times 10^3$ kg/m³, length of the sleepers $a_s = 2.6$ m, height of the sleepers $h_s = 0.2$ m, width of the sleepers $b_s = 0.26$ m, shear modulus of the ballast $G_B = 18 \times 10^7$ N/m², width of the ballast $a_B = 3.6 - 5.6$ m, height of the ballast $h_B = 0.3$ m, shear modulus of the soil $G = 8 \times 10^7$ N/m², shear wave velocity of the soil $v_S = 200$ m/s, mass density of the soil and ballast $\rho = 2 \times 10^3$ kg/m³, Poisson’s ratio of the soil and ballast $\nu = 0.33$, hysteretic damping of the soil and ballast $D = 2.5$ %, hysteretic damping of the elastic elements $D_p = D_s = 10$ %.

2.3 Results of a parameter study

The ground vibration ratios between the isolated and the unisolated track are presented in Figure 3a-f for some of the parameter variations of [8]. The most important parameter is the stiffness of the under sleeper pad which is varied from 25 to 200 kN/mm (Fig. 3a). The ground vibration ratios start with a value close to $v_{I}/v_{U} = 1$ at low frequencies. A resonance amplification is reached at frequencies between 25 and 80 Hz depending on the pad stiffness. At about the 1.5-fold of the resonance frequency, the ground vibration ratios are lower than $v_{I}/v_{U} = 1$ and the reduction of the amplitudes starts. The ground vibration ratios decrease rather strongly down to values from $v_{I}/v_{U} = 0.1$ to 0.01 at 160 Hz. The lowest
Figure 3. Ground vibration ratios of isolated tracks to unisolated tracks, a) variation of the under sleeper pad stiffness $k_S = □ 25$, ○ 50, △ 100, + 200 kN/mm, b) variation of the sleeper mass $m_S = □ 75$, ○ 150, △ 300 (standard), + 600 kg, c) variation of the wheelset mass $m_W = □ 1000$, ○ 1500, △ 2000, + 3000 kg, d) variation of the shear wave velocity of the soil $v_S = □ 100$, ○ 150, △ 200, + 300, × 500 m/s, e) variation of the under sleeper pad stiffness as in (a) but with wide sleepers on ballast, e) variation of the under sleeper pad stiffness as in (a) but with wide sleepers on a slab track.

resonance frequency yields the best mitigation of ground vibrations.

Figure 3b shows the influence of the mass of the sleeper. The standard mass is that of a concrete sleeper. A quarter of that represents a wooden sleeper, a half of the mass is related to a sandwich sleeper were the pad is placed in the middle of the concrete sleeper. The best mitigation results are achieved with a double mass. The resonance frequency can be reduced from 35 Hz to 28 Hz and the high-frequency amplitude ratios are considerably lower.

The next two figures demonstrate the influence of parameters which cannot be changed, the wheelset mass and the stiffness of the soil. If the wheelset mass is increased from 1000 kg to 3000 kg (Fig. 3c), the resonance frequency is clearly reduced down to 25 Hz, and this gives a better reduction in the mid-frequency range of 50 to 100 Hz. The influence of the wave velocity of the soil can be found at mid and high frequencies in Figure 3d. A stiff soil with high wave velocity yields a higher resonance amplification.

As a possible mitigation solution, wide sleepers of double width and double mass are considered in Figure 3e. The higher mass yields lower resonance frequencies compared to Figure 3a (for example 23 Hz compared to 28 Hz for the softest under sleeper pad) and related to that, some better reduction effects are expected. Finally, wide sleepers on a slab track have been investigated (Fig. 3f). The resonance frequencies are very similar compared to the ballast track with the same wide sleepers (Fig. 3e). It has been found in [9] that the stiffness of the track element below the under sleeper pads has no importance for the mitigation of ground vibration. The same reductions are achieved for the wide sleepers and under sleeper pads above a concrete slab, an asphalt layer or the ballast.

Similar investigations have been performed for elastic rail pads [7], under ballast mats [5] and floating slab tracks [6].

3 LABORATORY TESTS

Laboratory tests of different sleepers and different under sleeper pads have been carried out in the laboratories of the BAM [10,11]. According to the results of the numerical studies, heavy and wide sleepers and soft under sleeper pads are the matter of interest. The wide sleeper type was also tested in combination with a slab track solution. For the ballast track solution, three different types of under sleeper pads (stiff, medium, soft) and a new sleeper type (the heavy concrete sleeper B90.2) have been investigated. A wide concrete sleeper BBS3.1 and two additional under sleeper pads have been tested for the application on slab tracks.

3.1 Tests on wide and heavy concrete sleepers

Figure 4. Laboratory test of a heavy sleeper, static loading at the rail seat section.
For the sleepers, static tests (Fig. 4), dynamic tests and a fatigue test (Fig. 5) have been carried out according to EN 13230-2 [12]. The rail seat section of the sleeper gets a positive moment due to wheel passage and is tested statically and dynamically. The centre of the sleeper is loaded for a negative moment (static tests). 20 pre-stressed monoblock heavy concrete sleepers B90.2 and 20 pre-stressed monoblock wide concrete sleepers BBS3.1 have been tested. The failure loads for the rail seat section were about 550 kN and 650 kN for the heavy and the wide concrete sleepers. The fatigue tests have been carried out with 2 million cycles between 50 and 128 kN or 50 and 176 kN, respectively. Crack detection is an important task for both, the static and the fatigue tests.

3.2 Tests on stiff and soft under sleeper pads

For the examination of the under sleeper pads, tests for the static and dynamic bedding modulus (Fig. 6), fatigue strength, bond strength, shear strength and the freeze-thaw resistance were carried out according to DIN 45673-6 [13].

The measurement of the static bedding modulus is presented in Figure 7a. Three load cycles from zero (minimum) stress to maximum stress are applied and two secant moduli are evaluated from the third increasing load curve. The dynamic (high-frequency) modulus is measured under a constant pre-load and small amplitude cycles (Fig. 7b). Static and dynamic tests display some hysteresis indicating the visco-elastic behavior of the material. Due to that, different moduli are measured under different test condition which will be demonstrated by the softest rail pad. The lowest bedding modulus of $C_{stat} = 0.025$ N/mm$^3$ is measured with 10 minutes rest time for the maximum load. The static bedding modulus is somewhat higher at $C_{stat} = 0.029$ N/mm$^3$ for medium ballast compaction, (for high ballast compaction it is 0.038 N/mm$^3$). A similar procedure with faster load cycles yields the low-frequency bedding modulus of $C_{low} = 0.039$ N/mm$^3$ (at 20 Hz). The high-frequency bedding modulus under pre-load (as described above) is $C_{dyn} = 0.082$ N/mm$^3$ (at 40 Hz). These relations are typical for all measured under sleeper pads.

The static tests of all under sleeper pads are presented in Figure 8. All under sleeper pads on ballast (the ballast plate) show an increasing stiffness with increasing static load (Fig. 8a,b). The under sleeper pads on a slab track (a plate, Fig. 8c) do not display such a clear non-linear effect and have an almost constant stiffness. The following static bedding moduli $C_{stat}$ (medium ballast compaction) have been measured: 0.03, 0.05, and 0.10 N/mm$^3$ for the ballasted test tracks in Germany, 0.11, 0.12, 0.13 N/mm$^3$ for the ballasted test tracks in Switzerland, 0.06 and 0.85 N/mm$^3$ for the slab track solutions. The most important values for the mitigation effect are the dynamic bedding moduli $C_{dyn} = 0.082$, 0.146, and 0.332 N/mm$^3$ for the German ballast-track solutions and $C_{dyn} = 0.25$ N/mm$^3$ for the slab track solution.
Figure 8. Static loading tests of different under sleeper pads, load-displacement curves for a soft, a medium and a stiff under sleeper pad (a), for three stiff under sleeper pads of the swiss test site (b), and for a soft and a stiff under sleeper pad for slab tracks (c).

The big difference between the static and the high-frequency dynamic bedding moduli is stronger than the difference between the tangent and the secant modulus in the non-linear static test results. It is also stronger than the difference between static and low-frequency load application which is mentioned in [13]. (“In the frequency range up to 1 Hz the stiffness of elastomeric structural elements is often strongly dependent on the frequency. This is due to the fact that these materials tend to creep under load (increasing deformation with longer load times) and then relax when the load is removed (complete recovery, e.g. in elastomeric elements) ... The kinetic stiffness of elastomers is larger, in some cases very much larger than the static stiffness.”)

As a conclusion of the laboratory tests, the combination of the heavy sleepers and the soft under sleeper pads has passed all tests so that possible mitigation measures at track have been found. In the field test, different under sleeper pads with standard sleepers, heavy sleepers as well as heavy and wide sleepers have been installed and tested.

4 FIELD MEASUREMENTS

Field measurements have been performed at more than twenty sites in Germany and Switzerland. The measurements for each site include the determination of soil properties from artificial excitation (usually a hammer excitation) and the measurement of train induced ground vibration. The comparison of the train induced vibrations of different sites allows to determine the effects of mitigation measures. The soil properties help to interpret well the differences measured at different sites. The equipment is installed in a measurement truck (Figure 9), and the measurements system can measure up to 72 sensors simultaneously so that two neighbouring track sections, for example an isolated and an un-isolated track section can be measured at the same time.

Figure 9. Field measurements near Regensburg, measuring truck, measuring axis and a passing ICE.

4.1 Soil properties measured by artificial wave excitation

The soil properties of a site are measured on an axis of equidistant located sensors (geophones). Different methods are available to evaluate the measuring data. The most important parameter is the Rayleigh wave velocity of the soil. The simplest evaluation method is shown in Figure 10. The seismogram or time history diagram where the time histories of each sensor are plotted corresponding to the distance to the source. The propagating waves can be observed and the wave velocity determined from the time delay between similar characteristics of the time records (zeros, maxima, minima). For the measuring site of Herne, a wave velocity of 240 m/s can be found.

Another method of determination of the wave velocity is the wavenumber method. The wavenumber transform of all amplitudes of all sensors yields a frequency-wavenumber spectrum which is displayed in Figure 11. As the y-axis is presented as a wave velocity, the diagram can be directly read as a dispersion function, that is the wave velocity of the soil as a function of the frequency. At Herne, the soil is almost
homogeneous. At Frequencies above 20 Hz the wave velocity is almost constant at 240 m/s. At lower frequencies, the wave velocity increases with decreasing frequency. Such a dispersion (frequency-dependent wave velocity) is due to a higher stiffness at greater depths of the soil. A soil model can be approximated to this experimental dispersion curve. A thick layer of 8 m above a stiff soil is identified for the Herne site. A stiff half-space under such a thick layer has usually little influence on the vibration of the surface in the frequency range above 10 Hz [4].

Whereas the wave velocities provide information about the stiffness of the soil, the attenuation of the amplitudes is used to determine the material damping of the soil (Fig. 12). The damping at the Herne site is evaluated as $D = 5...9\%$, which is rather high.

Some more methods are used to evaluate the wave velocity of the soil, the correlation method in time domain, the SASW (Spectral Analysis of Surface Waves), and the SPAC (Spatial AutoCorrelation) method in the frequency domain. All methods confirm the almost homogeneous nature of the soil at the Herne test site.

### 4.2 Train induced ground vibration

The train induced ground vibration is measured on an axis perpendicular to the railway track. A long axis with many measuring points is preferred. It would be advantageous if the same axis for the soil properties and the train vibration could be used and a maximum of sensors is available for both evaluations. By this, the regularity of all measuring points can be checked. In fact, the measurement layout has to follow the

![Figure 13](image-url)
Proceedings of the 9th International Conference on Structural Dynamics, EURODYN 2014

4.3 Evaluation of mitigation effects

The train induced ground vibration have been averaged for each train group and each measuring point. These average amplitudes are compared as the ratio of $v/I/\nu_{U}$ of the isolated to the un-isolated track for each train group and each measuring point. Finally an average of these ratios for all or some selected measuring points is determined. These ratios which describe the mitigation effect are presented in Figures 14a to 14c for the measuring sites Regensburg, Lengnau, and Rubigen. At all places, a stiff or very stiff rail pad was installed. Therefore the mitigation effects are found at frequencies higher than 64 (Fig. 14a), 80 (Fig. 14b) or even 100 Hz (Fig. 14c). The maximum reduction is $v/I/\nu_{U} = 1/3$. The results in Figure 14a are for three different stiff under sleeper pads and the high-frequency reductions reflect the stiffness order of these pads. The softest under sleeper pad yields the lowest amplitude ratios. This can best be seen at the sleeper-passage frequency at 64 Hz where the clearest mitigation effect is observed. The reduction (or amplification) at low and high frequencies, where the train induced ground vibration is small, can be influenced by other environmental sources or by the layering or damping of the soil [4].

4.4 Mitigation effects of heavy sleepers and soft under sleeper pads

The mitigation effects of the heavy sleepers and the soft under sleeper pads, which have been tested in the laboratory, have been determined by a special artificial excitation, a dynamic shaker excitation under realistic static loads [14]. At first, the measured low shaker-track resonance frequency is a clear

Figure 14. Measured ground vibration ratios of isolated track to un-isolated track, a) three different stiff to very stiff under sleeper pads near Regensburg, b) two different stiff under sleeper pads in Lengnau, c) very stiff sleeper pads under a switch in Rubigen, average of several train passages and measuring points.

local conditions so that the soil properties are often measured along the track and the axis for train vibration is sometimes shorter than desirable.

As an example of train induced ground vibrations, the results at the Regensburg site are presented as third of octave band spectra in Figure 13. The spectra typically increase with frequency at low frequencies, a maximum is reached at mid frequencies, and the amplitudes decrease for high frequencies. (The pronounced peak at 64 Hz in Figure 13a is due to the sleeper-passage excitation). The low-frequency increase is almost the same for all measuring points, whereas the decrease at high-frequencies due to the material damping is stronger for the far-field points. One might expect that the results about the mitigation effect of any measure will be more clear in the frequency range of high amplitudes. That means clear results are expected at mid frequencies for all measuring points, and also at high frequencies for near-field points. A first comparison of isolated and un-isolated track can be done by these spectra. More detailed results can be achieved by additional evaluation for example of amplitude ratios.

Figure 15. Measured ground vibration ratios of isolated track to un-isolated track, artificial excitation in Herne on different isolated tracks, + heavy sleeper on medium soft pads on ballast, △ wide sleeper on soft pads on ballast, ○ wide sleeper on medium soft pads on ballast, □ wide sleeper on stiff pads on slab track.
indication of the successful mitigation. Resonance frequencies of 36, 41, 49 and 58 Hz have been measured for the different wide and heavy sleepers and different under sleeper pads. The amplitude reduction measured at a free-field point 12 m away from the track (Fig. 15) yields values of less than $v\sqrt{v/c} = 1/10$ (-20 dB) for the wide sleeper on the soft under sleeper pad ($\Delta$) and $v\sqrt{v/c} = 1/3$ (-10 dB) for the heavy sleeper (+).

The measured resonance frequencies could be established in the calculations if the dynamic pad stiffnesses of the laboratory tests are modified. The isolated wide and heavy sleeper track showed a lower resonance frequency and a lower ground vibration, the isolated heavy sleeper track showed a higher resonance frequency and higher amplitudes, whereas both heavy sleepers on comparable sleeper pad stiffnesses should give the same good mitigation effect.

5 CONCLUSION

Mitigation measures for railway tracks have been investigated by numerical simulation, laboratory experiments, and field tests. Good mitigation measures have been achieved, heavy or wide sleepers on soft under sleeper pads. The laboratory tests help for the choice of the under sleeper pad as a compromise between sufficient stiffness for the static train load and a high dynamic compliance for a good mitigation effect. Field tests can verify the predicted dynamic reduction effects and sometimes unveil additional non-dynamic reduction effects, e.g. reduced track settlements and reduced alignment errors. At the BAM, the three tasks theoretical analysis, laboratory and field tests are considered comprehensively.

ACKNOWLEDGMENTS

The BAM work for the RIVAS project has been accomplished by L. Auersch (numerical studies), E. Knothe, R. Makris and E. Kretzschmar (laboratory tests), S. Said (field tests), W. Rücker (project leading) and has received funding from the European Union Seventh Framework Programme under grant agreement n° 265754. The work package 3 “Mitigation measures track” has been organized by E. Bongini (SNCF), B. Asmussen and W. Behr have been the coordinators of the whole research project RIVAS. The test specimen of the different sleepers have been developed by A. Pieringer (Railone) The test track has been built at and by Eiffage Rail (S. Schwieger). The field measurements have been initiated by R. Müller (SBB) and R. Garburg (DB).

REFERENCES


