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PREDICTED ACOUSTIC EFFECTS OF RAILWAY BALLAST

K. Attenborough (1), P. Boulanger (1), H. A. Holties (2)

(1) The Open University, Engineering Mechanics Discipline, Milton Keynes, England
(2) M + P Raadgevende ingenieurs bv, Aalsmeer, The Netherlands

1. INTRODUCTION

Noise generated by railway traffic can be a cause of considerable annoyance for people living or working in the vicinity of railway lines and railway yards. Therefore, possibilities to reduce railway noise are studied extensively. It is known that the type of bedding material influences the noise levels that occur at the side of the railway track. In particular, compared to concrete slab tracks, bedding material consisting of ballast is found to give rise to reduced noise levels. However, in designing railway tracks with ballast as bedding material, the acoustical properties have not been an issue for study so far. The design parameters are mainly related to the structural properties. Ballast is a porous material consisting of stones with a diameter between approximately 30 and 63 mm. Due to the relatively large stones, the flow resistivity is very small for normal ballast, thus giving rise to sound propagating through the ballast parallel to the surface. The ballast, therefore, acts acoustically as a non-locally reacting material. To study the mitigation of noise dependent on ballast characteristics, a model for sound propagation over porous material has been developed. The model has allowed investigation of the effect that modified acoustical properties of the ballast material have on the reduction of railway noise. This study has resulted in recommendations for the design of acoustically optimal ballast. The project has been commissioned by NS Technisch Onderzoek on behalf of the European Rail Research Institute.

2. MODEL FOR THE ACOUSTICAL CHARACTERISTICS OF POROUS MATERIALS

A number of models describing the acoustical properties of porous materials in terms of one or more physical parameters are available. The analytical model based on sound propagation in parallel sided slits [1]-[2] has been chosen to calculate the acoustical properties of ballast. The relevant acoustical parameters to be determined for a porous material are the characteristic impedance Z and the propagation constant k. In the model used here, these are a function of the angular frequency ω, the porosity Ω, the tortuosity q, and the flow resistivity σ:

$$k = \omega\sqrt{\rho_b(\omega) / S_b(\omega)}\,; \qquad (1)$$

$$Z = \sqrt{\rho_b(\omega) S_b(\omega)}\,. \qquad (2)$$

where the complex density $\rho_b(w)$ and the complex stiffness $S_b(w)$ are given by, respectively:

$$\rho_b(\omega) = (q^2 / \Omega)\rho_0\left[1 - \tanh(\lambda\sqrt{-i}) / (\lambda\sqrt{-i})\right]^{-1}, \qquad (3)$$

$$S_b(\omega) = (\gamma P_0 / \Omega)\left[1 + (\gamma - 1)\tanh(N^{1/2}\lambda\sqrt{-i}) / (N^{1/2}\lambda\sqrt{-i})\right]^{-1}; \qquad (4)$$

$$\lambda = \sqrt{\frac{3\omega\rho_0 q^2}{\Omega\sigma}}\,.$$

Here, ρ_0 denotes the density of air, $i = \sqrt{(-1)}$, P_0 the pressure of the atmosphere, $\gamma = 5/3$, and N the Prandtl number for air.

For large flow resistivities (e.g. for soils) the sound incident on the surface is strongly refracted downward and normal to the surface. In such cases the surface is locally reacting. For the low values of ballast flow resistivity, propagation of sound parallel to the surface can no longer be neglected when the angle of incidence is not equal to zero. The surface is non-locally reacting and the normal surface impedance is a function of the angle of incidence.

When sound waves are incident on a uniform hard backed layer of porous material with finite thickness, the normal surface impedance is given by:

$$Z_{s,1} = \left(Z / \cos(\theta_t)\right) / \tanh(-ikd\cos(\theta_t)); \qquad (5)$$

$$\cos(\theta_t) = \sqrt{(1-(k_0/k)^2 \sin^2\theta)},$$

where θ denotes the angle of incidence measured from the normal, and k_0 the propagation constant for airborne sound waves. The finite thickness of the layer gives rise to interference effects, that lead to a frequency dependent sound absorption. The ballast considered in this work includes two layers of porous material. The normal surface impedance for such a composite (hard backed) layer is given by:

$$Z_{s,2} = Z_{n1}\frac{Z_{n2} + Z_{n1}\tanh(\kappa_{n1})\tanh(\kappa_{n2})}{Z_{n1}\tanh(\kappa_{n2}) + Z_{n2}\tanh(\kappa_{n1})}; \qquad (6)$$

$$Z_n = Z / \cos(\theta_t);$$

$$\kappa_n = -ikd\cos(\theta_t),$$

where the indices 1 and 2 refer to the porous material in the upper and lower layer, respectively.

3. CALCULATION OF SOUND PROPAGATION OVER BALLAST

To allow the geometry of a railway track to be taken into account, calculations have been performed using the boundary element method. With this method, the sound field is found by calculating the field at the boundaries of the volume that is considered, under the assumption of a homogeneous atmosphere. With the solution known at the boundary, the sound field can be calculated at an arbitrary point using analytical formulas for sound propagation in homogeneous air. The shape of the boundaries is, in principle, arbitrary. The code used in this study was originally developed to calculate the insertion loss of road barriers [3]. The code is two-dimensional in the sense that only situations and sound sources can be modelled that show no variation along one axis. An infinite flat or profiled ground surface can be modelled. The acoustical impedance can be chosen independently for each surface element of the profile. Furthermore, it is possible to determine the surface impedance for each element using a dominant angle of incidence. The dominant angle of incidence is calculated from the relative position of the sound source and the surface element. The code has been extended to evaluate sound propagation over ballast. The porous material model described earlier has been included, and the surface impedance calculations for a non-locally reacting composite layer have been implemented.

4. RAILWAY BALLAST

The type of ballast found in the Dutch railway tracks [4] is considered in this work. A draft European standard for unbound aggregates to be used as railway ballast [5] gives requirements for applicable materials that are similar to materials currently in use in the Netherlands. A number of stone size distributions is being used in ballast. A most common distribution involves stones diameter of 30 up to 63 mm. Smaller stone sizes can give rise to problems with the drainage, while larger stones can lead to problems with the construction and maintenance of the railway track. The porosity of a volume filled with stones depends on the distribution of stone sizes, on the rate of compaction, and on the typical shape of the stones. For railway ballast, the porosity is reported [4] to vary from 0.3 to 0.4. In this study, the flow resistivity [6] is computed from:

$$\sigma = \mu / K \ \mathrm{Ns/m^4}; \tag{7}$$

$$K = 0.00946(1-\Omega)^{2/3}\left[\frac{0.904}{(1-\Omega)^{2/3}} - 1\right]^2 D^2 \ \mathrm{m^2},$$

where *m* denotes the dynamic viscosity for air and *D* the mean particle diameter in meters.

The tortuosity [2] is obtained from the relation:

$$q^2 = \Omega^{-s}, \tag{8}$$

where *s* denotes the shape factor. Values of tortuosity up to 2 are expected for ballast.

5. RESULTS

The A-weighted emission spectrum for freight trains travelling at 100 km/h is used in the calculation of sound level differences. This spectrum is determined according to the Dutch Guidelines for the calculation of noise generated by railway traffic [7].

The normal ballast porosity is assumed to be 0.38. With a mean stone-size diameter of slightly less than 5 cm it follows from equation (7) that the flow resistivity is approximately 20 Ns/m^4. The tortuosity is assumed to be 1.622 and the ballast thickness is 0.5 m.

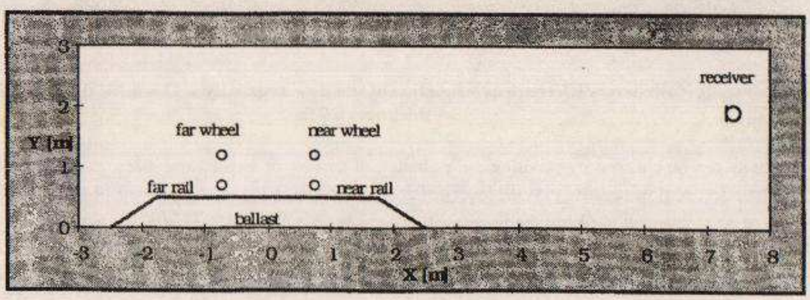

Fig. 1: Geometry used in the model calculations

Fig. 1 shows the geometry assumed for the railway track. The four noise sources studied are:

- the rail on the near side of the track
- the wheels on the near side of the track
- the rail on the far side of the track
- the wheels on the far side of the track.

The rail noise sources are modelled as infinite line situated 0.2 m above the ballast surface. Noise radiated by the wheels is represented by infinite line sources located 0.7 m above the surface. The attenuation is calculated from the noise level at 7.5 m horizontal distance from the centre of the track and 1.3 m height above the railhead. The flat ground surface is modelled to represent grassland using $\Omega = 0.4$, $q = 1.581$ and $\sigma = 200000$ Ns/m^4 and an infinite layer thickness. In the following, results showing the effect of normal ballast modifications will be presented. The level difference between the situation with normal ballast and the situation with modified ballast is shown in each subsequent figure. The level difference has been calculated for each of the noise sources separately. Negative values for the level difference correspond to lower noise levels in the case of modified ballast. In general, the impact of a modification will be greatest for sound propagating a long distance over ballast. Therefore, the modifications will have the largest effect on noise emitted by the rail on the far side. The effect of the wheel on the near side is limited since the noise emitted from this source is not reflected from the ballast surface in the direction of the receiver.

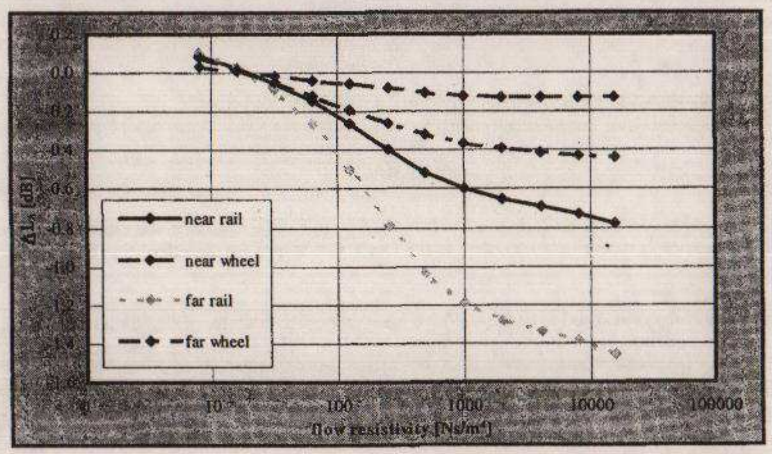

Fig. 2: Noise-level difference as a function of the flow resistivity s; $\Omega = 0.38$; q = 1.622; layer thickness = 0.5m.

The flow resistivity can be changed by choosing a distribution of smaller or larger stone sizes, as can be seen from equation (7). The effect of flow resistivity on the level difference is shown in Fig. 2. An increase of the flow resistivity leads to improved noise attenuation. When the flow resistivity reaches a value of 1000 Ns/m^4 or more, the noise is not much further reduced.

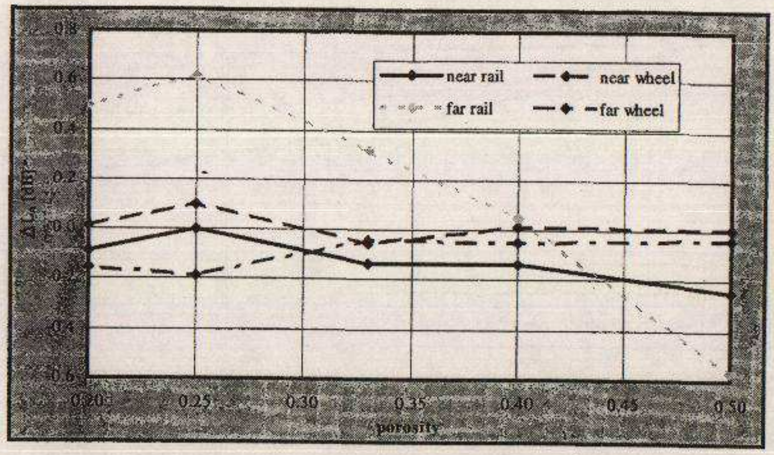

Fig. 3: Noise-level difference as a function of the porosity Ω; $\sigma = 20$ Ns/m^4; $q = \Omega^{-½}$; layer thickness = 0.5 m.

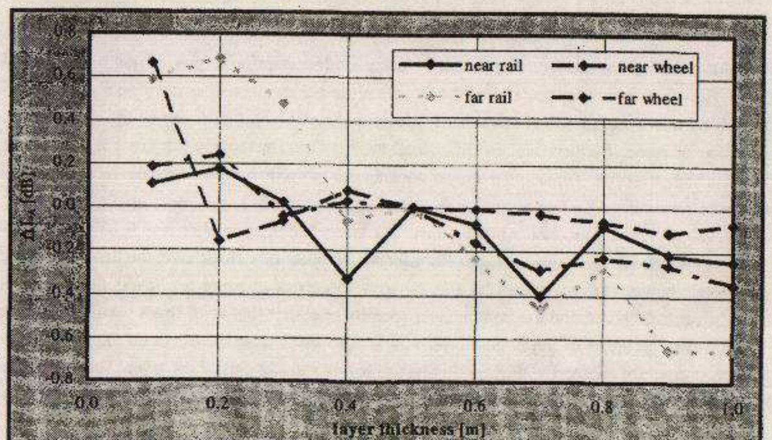

Fig. 4: Noise-level difference as a function of the layer thickness; Ω= 0.38; $\sigma = 20$ Ns/m^4; q = 1.622.

The porosity of ballast is determined by the uniformity of the distribution of the stone size, the rate of compaction, and the typical shape of the stones. The tortuosity is a function of porosity and shape factor (See equation (8)). The effect of varying the porosity is shown in Fig. 3.

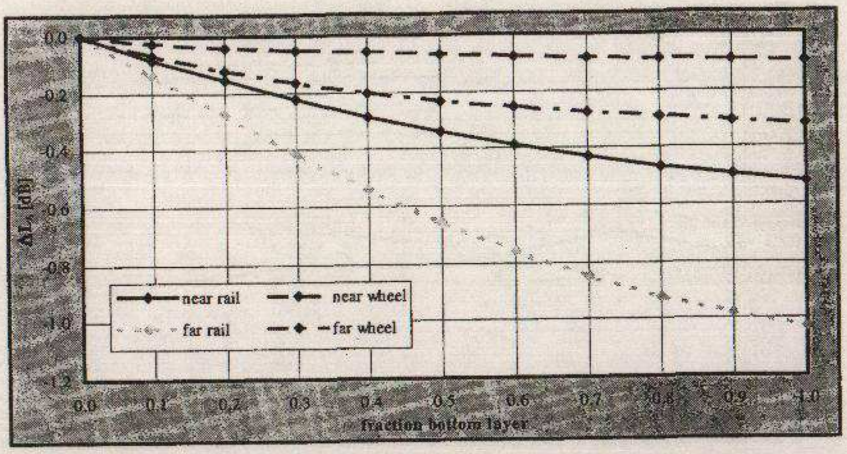

Fig. 5 Noise-level difference as a function of the fraction of the total ballast thickness that is occupied by the bottom layer. Top layer: Ω= 0.38; σ = 20 Ns/m^4; q = 1.622. Bottom layer: Ω= 0.38; σ=500 Ns/m^4; q = 1.622.

Optimal attenuation of noise emitted by the rails can be achieved by choosing a material for which the porosity is as large as possible. However, a porosity larger than 0.4 is difficult to achieve and does not give rise to a much improved attenuation of railway noise. Additional calculations not presented here show that changing the tortuosity does not lead to a net attenuation increase. Furthermore, modifications to these parameters do not have a large effect on noise propagating from a higher source. Increasing the layer thickness to more than 0.5 m does not have a large effect on the noise level as can be seen in Fig. 4. The attenuation starts to decrease for a layer thickness smaller than 0.5 m. However, the attenuation shows a dramatic increase when the layer thickness becomes smaller than 0.2 m, case which is not of relevant for railway ballast. For stones with a mean diameter on the order of a centimetre, the flow resistivity is 25 times as large as for normal ballast (See equation (7)). Fig. 5 shows the effect of using two layers of ballast where the top layer is taken to be normal ballast, and the bottom layer consists of stones that are 5 times smaller. The fraction of the total layer height that is occupied by the bottom layer is varied to investigate the effect on the noise attenuation. It is found that the attenuation can be improved by modifying the ballast only in part of the layer. The same noise reduction as obtained when modifying all of the ballast can be achieved within 0.2 dB by modifying the lower or upper 75% of the ballast.

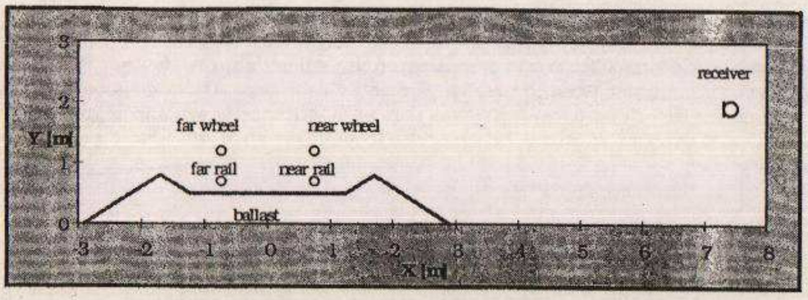

Fig. 6: Ballast with protrusion up to 0.3 m above the surface.

Fig. 6 shows ballast profiling a small protrusion beside the sleepers. The height of the protrusion is 0.3 m and the embankment has been made 0.4 m wider on both sides in order to keep the slope previously used. The acoustical parameters are chosen to represent normal ballast. In table I the noise level difference is presented for the two cases of protrusion heights 0.2m and 0.3m when compared to normal ballast without protrusion. It has been assumed in the calculation that noise transmitted through the protrusion is negligible.

Table I: Noise level difference for embankment with protrusion

	near rail	far rail	near wheel	far wheel
protrusion 0.2 m	-2.0	-1.0	-0.1	0.2
protrusion 0.3 m	-3.2	-1.6	-0.5	0.2

It is not surprising that the effect of the protrusion on noise emitted by the wheels is minimal. However, rail noise emission can be attenuated significantly by use of small ballast protrusions. The ballast protrusion acts as a noise shield, and the effect is largest for the rail on the near side of the railway track.

6. CONCLUSIONS

The design of the ballast can be improved to reduce railway noise, but the improvement is limited due to the intrinsic sound absorbing nature of ballast. Larger porosity and larger flow resistivity lead to lower noise levels. The porosity can be increased by using stone sizes as uniform as possible and by compacting. No improvement can be obtained with a porosity above 0.4. Decreasing the stone sizes increases the flow resistivity but might impede drainage. Small stones might also be too sensitive to the air displacement created by passing trains and the choice of size is therefore a compromise between optimum acoustical properties and engineering demands. Part of this problem might be solved by a composite arrangement in which the top 25% of the ballast bed is made with normal stones but the lower 75% of the ballast bed consists of stones that are 5 times smaller than normal. This should achieve a noise reduction almost equivalent to the one obtained with ballast containing only the small stones.

Further reduction of railway noise can be achieved by ballast profiling without the need of modifying the ballast material. Small protrusions beside the sleepers show some shielding of the noise emitted by the rails. Greater noise reductions seem possible by profiling than by optimising porosity or flow resistivity. However, the results are based on the assumption of negligible sound transmission through the protrusions. The model should be improved by allowing transmission through the protrusions. It was shown that increasing flow resistivity and ballast thickness independently lead to increased attenuation, but more calculations are needed to verify that it is possible to optimise both simultaneously.

7. REFERENCES

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