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NOISE FROM UNDERGROUND RAILWAYS - A 'STATE OF THE ART' REVIEW

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1. INTRODUCTION

The subject of structure-borne noise from underground railways is not only a very interesting one for acousticians, it is also an important one for the future development of our cities. We all know of the present strong interest in different kinds of rail traffic, not least with respect to mass transportation in cities. At the same time, we also see a pronounced interest in developing more compact cities in order to reduce the traffic work. Accordingly, new railway and subway lines are being built close to existing buildings and vice versa. The case of new houses close to new railway and subway lines is also of great importance.

The economic importance of the subject is enhanced by another factor. It is obvious that "new" types of noise sources are often regarded in different, and more severe, ways than old, well-known ones. The Swedish immission limits for railway noise can be taken as a typical example. The air-borne sound from trains is well known since more than a century. Thus the air-borne noise is regarded as an old source type and the immission limit is comparatively high: 45 dB(A) (maximum level indoors from 7 pm to 7 am, time weighting F or S). The structure-borne sound has become important only in later years and is consequently regarded as a new source type. The immission limit for ground-borne noise is in Sweden usually 10-15 dB lower than that for air-borne noise.

In order to obtain an overview of the field, a literature search has been carried out. It is not the purpose of this paper to present an account of the contents of the 140 documents found. However, the search gave rise to question marks on one particular aspect which is also thought to be of fundamental importance, namely the influence of the ground impedance. Thus, the present paper is confined to this topic.

2. MODELS FOR SOFT GROUND

Two different types of models for the prediction of noise from underground railways can be found in the literature. The older one is illustrated in Fig. 1. In this case, see e g [1-6], the response of the building is expressed as a transverse velocity of the basement floor (or wall), v_B. According to the cited references, the velocity v_B can, with some variations, be taken as

$$10 lg \frac{<v_T^2>}{<v_B^2>} = C_1 + C_2 + C_3, \tag{1}$$

where v_T is a suitably defined transverse velocity of the tunnel, and where C_1 describes the coupling between the tunnel wall and the ground, C_2 the effects of propagation to the basement wall, and C_3 the coupling between the field of the ground and the bending wave field of the basement floor or walls.

An underlying assumption is in this case that the source can be regarded as a velocity type of source, that is, the impedance of the source is much higher than the characteristic impedance of the P- and S-waves of the ground. Another important assumption is that the relevant impedances of the building are high in comparison with those of the ground.

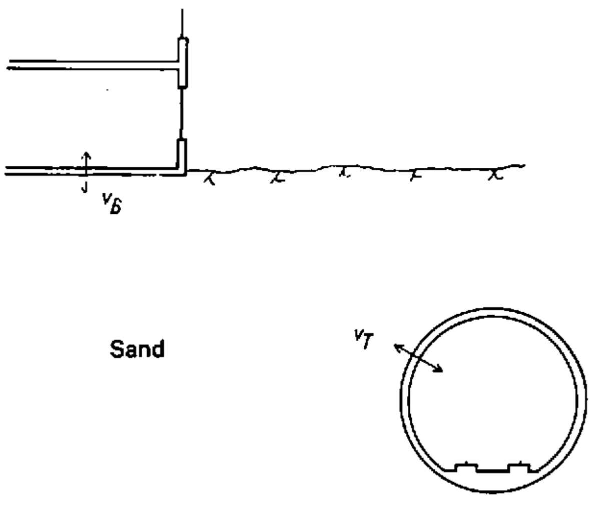

Fig. 1. Illustration of the prediction model used for soft ground.

3. MODELS FOR STIFF GROUND

Fig. 2 illustrates another type of model. The volume waves of the ground are in this case assumed to have a high characteristic impedance compared with those of the source and the building. The source strength can in this case be presented as velocity components of the ground at a certain distance from the tunnel bottom. It is difficult to generalize the results from different sources as the source strength is strongly dependent on details such as the amount of ballast, if any, between sleepers and tunnel bottom.

The assumption of high ground impedance implies that the ground, seen from the building, must be regarded as a constant velocity type of source. Thus, the power P transmitted into the building can in principle be written as

$$P = v_B^2 Re\{Z\}, \tag{2}$$

where v_B is a suitably defined velocity and Z is the input impedance of the building in a direction corresponding to this velocity. It is now seen that a major part of the power is transmitted into the building along a path where the building impedance is high. One obvious path of this type is that which involves a vertical ground velocity component which couples to longitudinal plate waves in the load-bearing walls (or columns) of the building.

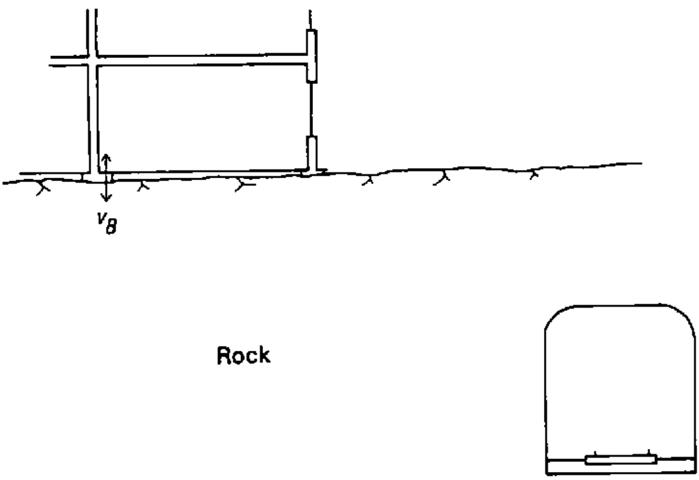

Fig. 2. Illustration of the prediction model used for stiff ground.

4. SOUND PROPAGATION IN BUILDINGS ABOVE TUNNELS

In the case of soft ground, the sound from the tunnel couples to bending waves in the basement floors and walls of the buildings. The transmission upwards in a building can then be predicted in the same way as, for instance, the flanking transmission between two rooms when calculating the field sound reduction index. For most building constructions used in practice, predictions and measurements show that the velocity level of a radiating surfaces higher up in the building will be lower than that of the primarily excited floor and walls. The model measurement results presented in [6] can be taken as an example: the level of the basement floor minus that of the first floor is at low frequencies 5-10 dB with an increasing trend towards higher frequencies.

It has been observed in the field that the level of the first floor is sometimes higher than that of the basement floor. This has been attributed to the presence of resonances [2], [4]. It should, however, be noted that no increase of this kind has been observed when a floor is excited higher up in a building [7].

It seems probable that the reported level increase is, at least in some cases, due to another effect. If the impedance of the ground is high, the sound will propagate upwards in the form of longitudinal and transverse plate waves. In the present case only the longitudinal waves will be regarded due to their strong coupling to the bending wave fields of the floors (the transverse waves can, of course, be important if they can couple to strongly radiating bending waves in perpendicular walls).

A simple theoretical model for the transmission of longitudinal waves upwards in a building has been presented in [8]. This mode is based on the "Ketten-Leiter" theory. In order to apply this model for a prediction of the level of a floor from the free vertical velocity of the ground, it is assumed that

- the walls act as velocity sources on the floors,
- the velocity level of the floors can be estimated as in [9], p 333 (the floors are in the present types of buildings usually fairly large, 50-100 m^2).

Fig. 3 shows a comparison between predicted and measured level difference in a typical Swedish building with load-bearing walls. The calculations were carried out using the analytical expression for the loss factor in [9], p 486, the expression for the level decrease at a wall/floor junction in [8], and the input admittance of the plate given in [10].

It is seen that at low frequencies, the velocity level of the floor is some 7 dB higher than that of the ground, whereas it would have been at least 5-10 dB lower assuming a soft ground. As noise control measures are often designed using measured ground levels as a basis, it is realized that a misjudgement of the ground impedance can lead to a considerable underestimate of the noise in the building.

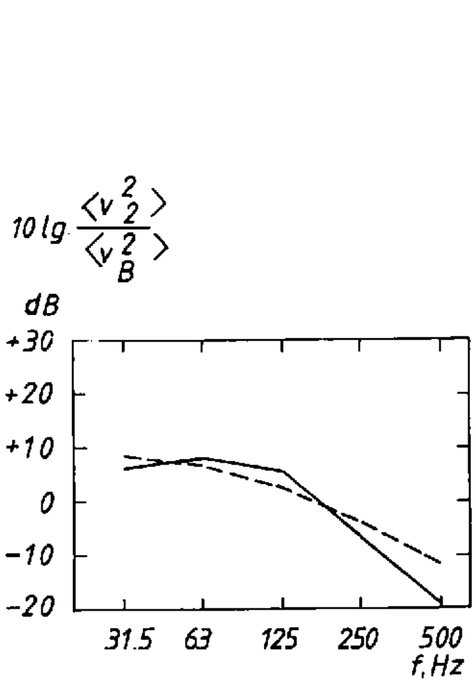

Fig. 3. Level difference between velocities of the second floor (v_2) and the building foundation (v_B). Solid line: measurement result; dashed line: predicted.

5. INSERTION LOSS OF FOUNDATION MATS

In the case of new buildings, a fairly common method to reduce the noise is to insert elastic members in the form of rubber cushions or foundation mats between the load-bearing parts of the building and the ground. The insertion loss of such a measure is often estimated using an one-dimensional mass-spring model. However, it is well known that such a model will give a substantial overprediction of the insertion loss, especially in the case of foundation mats, and it is also known that several consultants tend to rely more on empirical results than on results obtained from the mass-spring model.

However, a simple model for the behaviour of the system including the elastic layer can readily be derived from the stiff ground model presented above. If it is assumed that the ground is stiff enough (in comparison with the stiffness of the elastic layer!), the insertion loss of the layer can be estimated as [9], p 374

$$R = 10lg(1+(\frac{\omega Z_1}{2s_2})^2), \tag{3}$$

where ω is the radian frequency, Z_1 is the characteristic impedance of the longitudinal wave in the wall, and s_2 is the stiffness of the layer.

Fig. 4. shows the calculated insertion loss using the two approaches. The elastic layer is assumed to be 25 mm thick and with a Young's modulus of 5.5 MPa. The static load is such that the mass-spring resonance of 10 Hz. It is seen, that the use of the wave-guide approach gives a considerably lower estimate of the insertion loss of the layer.

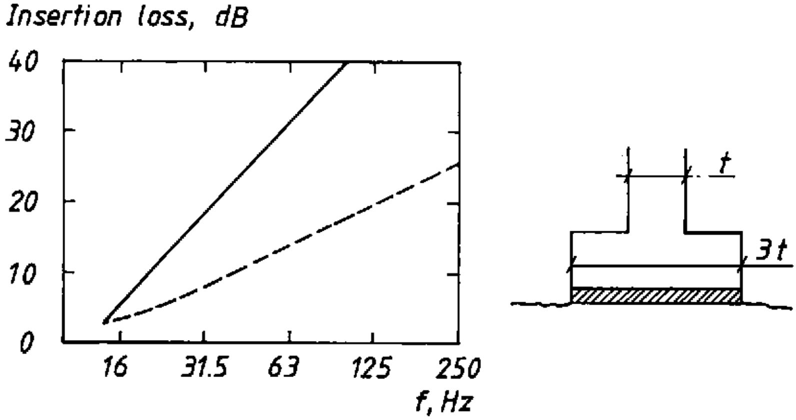

Fig. 4. Calculated insertion loss of foundation mat. Solid line: assuming single degree mass-spring system; dashed line: assuming transmission of longitudinal plate waves.

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