ENGINEERING TRANSACTIONS • Engng. Trans. • 48, 3, 273–282, 2000
Polish Academy of Sciences • Institute of Fundamental Technological Research
10.24423/engtrans.592.2000

REDUCTION OF TRAIN-INDUCED VIBRATION IN BUILDINGS

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There are many ways of reducing the transmission of train-induced vibration into buildings. One such measure is the use of floating-slab track whereby the track is mounted on a concrete foundation resting on isolation bearings. Impressive claims are often made regarding its effectiveness by referring to simple mass-spring models. However, some recent work, reviewed in the initial part of this paper, suggests that the effectiveness of floating-slab track for underground railways can be severely limited by interactions with the tunnel and surrounding soil.
The paper goes on to discuss base isolation of buildings as an alternative to vibration countermeasures at source. Again, simple mass-spring models are often used to make predictions of isolation performance which are far too optimistic. Alternative models are discussed with a view to developing a more appropriate means of assessing isolation performance

1. Introduction

Train-induced vibration in our cities is becoming an increasingly important issue due to increased public sensitivity to noise and vibration, together with more demanding legislation, and the pressure to expand rail networks and develop the existing urban sites. Such sites that remain are often close to surface or underground railways where ground-borne vibration can lead to unacceptable levels of noise and vibration within a building.

Modern construction techniques tend to exacerbate the problem. The trend is to build continuous light-weight structures with large floor spans and inherently low damping compared with older brick buildings. Thus modern construction methods alone tend to result in buildings which are more susceptible to vibration within the frequency range of concern, typically between 5 Hz and 200 Hz.

The problem is concerned with reducing the transmission of ground-borne vibration into a building, thereby reducing the levels of structure-borne vibration and re-radiated audible noise. The passing of a train is a transient event and the level of vibration reduction required is often open to question. Generally, however, the aim must be to reduce the disturbance, whether structural vibration or audible noise, below the general background level.

2. Floating-slab track

The most obvious action to take is to address the problem at its source and either control the mechanism by which vibration is generated or prevent vibration transmission from the rail track into the ground. An example of the latter is the use of Floating-Slab Track (FST) whereby the two rails are mounted via rubber railpads onto a concrete foundation-slab resting on rubber bearings or steel springs; see Fig. 1.

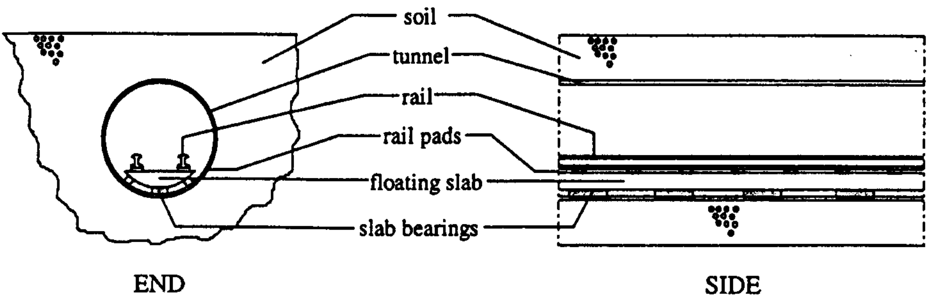

Fig. 1. The layout of floating-slab track for underground railway lines.

FST is often used with underground railways and is generally regarded as the most effective of vibration control measures which can be taken with the track. Examples in Europe include the Piccadilly Line, London; the Eisenmann track, Munich; and the Uderstadt, Cologne. Other examples can be found in Atlanta, Hong Kong, Melbourne, and Toronto.

2.1. Performance of floating-slab track

Proponents of FST often make impressive claims regarding its performance by referring to simple mass-spring models or ones based on Winkler-beam theory. In such models it is assumed that the slab bearings are sufficiently soft to decouple the slab from the tunnel, which can therefore be considered rigid. However, a recent analytical track-tunnel-soil model suggests that the performance of FST for underground railways can be severely limited by interactions with the tunnel and the surrounding soil.

FORREST and HUNT [1] model the rails and track-slab as infinitely-long beams with elastic layers representing the railpads and slab bearings. An infinitely-long cylindrical shell, surrounded by an isotropic viscoelastic continuum of infinite extent, represents the tunnel and surrounding soil. Thus the model accounts fully for the three-dimensional behaviour of a FST system. The reader is referred to the above paper for details concerning the computational aspects of the model.

Figure 2 shows a selection of the results for the r.m.s. soil displacements, due to a realistic rail-irregularity input spectrum, at increasing radial distances from the tunnel centre-line. Results are given for different slab-support 'frequencies', i.e. the natural frequencies of an equivalent Winkler-beam model. Close to the tunnel, it is evident that up to 5 dB reduction in vibration levels can be achieved through the use of FST. However, further away there is marginal, and sometimes adverse, effect. In addition, the small beneficial effect is only evident directly below the tunnel ($\theta = 0$ in Fig. 2); to the sides and above the track, the effect is insignificant. This is important since building foundations generally pass through these unaffected regions.

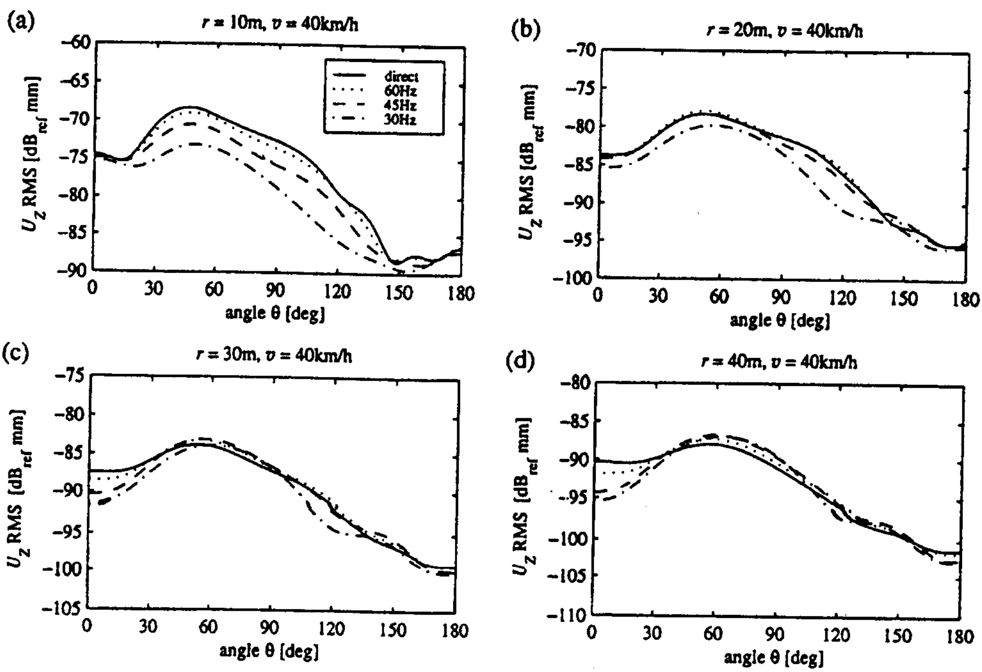

FIG. 2. RMS vertical soil displacements due to a train speed of 40 km/h at radii of (a) 10 m; (b) 20 m; (c) 30 m and (d) 40 m from the tunnel centre-line. The variation with angular position around the tunnel is given – $\theta = 0$ corresponding to vertically downwards – and the effect of different slab bearing stiffnesses is shown, including direct coupling to the tunnel.

Measures taken at the vibration source are not always possible; for example, new buildings are often constructed near the existing railways and it is difficult and expensive to take retrospective measures with the track or trains. In these cases, measures are restricted to the transmission path and the building itself. Often the ground vibration levels are considered large enough to justify the base-isolation of the building, i.e. the building is designed with vibration isolation bearings between the building and its foundation.

3. Base isolation of buildings

Base isolation of buildings is not a new concept [2]. Lead-asbestos isolation bearings were developed for some buildings in Manhattan, USA in the 1930s as a means of reducing an 'audible hum' transmitted through the rock on which the buildings were founded. The first example of a base-isolated building in the UK is Albany Court; a block of flats constructed on rubber bearings over St James Park Station, London in 1965. Since then numerous buildings have been constructed on rubber bearings or steel springs. Examples include office towers, concert halls and hospitals.

3.1. Modelling of base-isolated buildings

As in the case of FST, simple mass-spring models are often used to make predictions of isolation performance which are far too optimistic. The standard single-degree-of freedom (SDOF) model was originally used by Waller [2] when describing the design of Albany Court and is used extensively in the design of isolation bearings for machines. This, together with its inherent simplicity, has probably resulted in the model's popularity. However, the value of this model is very limited since it fails to describe some of the major features of a building's dynamic behaviour, in particular the flexibility and damping properties of the building and the effects of its foundation.

The model shown in Fig. 3, and discussed in detail by Talbot [3], considers a building founded on piles responding to a ground vibration-field consisting of surface Rayleigh waves. The model aims to capture the essential characteristics of a base-isolated building while being relatively simple and requiring little computational effort.

The building is represented by a two-dimensional portal frame, modelled using the dynamic-stiffness method. This accounts for the essential dynamic behaviour of the columns, floors and walls, and the coupling between them. The isolation bearings are represented by linear massless springs with hysteretic damping. There are three springs located on each pile cap to represent the vertical, horizontal and rotational stiffness of each bearing.

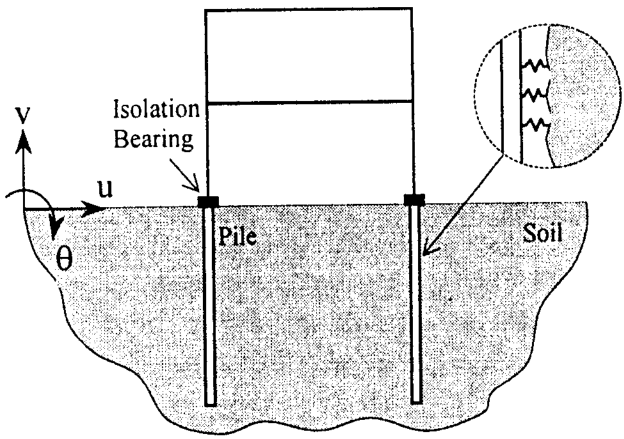

FIG. 3. Model of a base-isolated building. The building is represented by a two-dimensional portal frame while the piled foundation is based on a three-dimensional representation due to Gazetas and Makris. The pile-soil interface is represented by distributed springs and dashpots. For clarity, only the horizontal springs are shown.

The piles are modelled using the analytical approach of GAZETAS and MAKRIS [4, 5]. This approach uses the solutions for a linear-elastic axial column and Euler beam to model the axial and transverse behaviour of each pile. Wave propagation in the free field is accounted for by modelling the soil as a homogeneous isotropic linear-elastic half-space. In the near field, in both the horizontal and vertical directions, the pile-soil interface is modelled with continuously distributed linear springs and dashpots, the latter to represent radiation and hysteretic material damping within the soil. The model includes a representation of pile-soil-pile interaction, i.e. interaction between the piles through wave propagation in the surrounding soil.

Some typical results are given in Fig. 4 which shows the variation with frequency in the vertical and horizontal 'insertion loses' of the isolation bearings, i.e. the ratio of the response of the base of the building columns with and without the bearings in position. A concrete-framed building mounted on rubber isolation bearings is considered; the bearings are specified as '10 Hz', i.e. their vertical stiffness is such that an equivalent rigid-body model of the building would have an undamped natural frequency of 10 Hz. Since the building is responding to the passage of waves, the insertion losses calculated at the two building columns are slightly different; the insertion losses presented here are those calculated for the column first met by the waves.

As expected, there is an initial peak in the vertical insertion loss corresponding to the vertical 'bounce mode' of the building. Above this initial peak the bearings are effective although their performance is considerably poorer than a SDOF model would suggest. This is due to the local vibration modes of the building and piles reducing the efficiency of the isolation. Note that several of the smaller peaks are due to the phase difference in the motion of the piles.

The horizontal insertion loss shows a similar variation with frequency to that in the vertical direction. Coupling between the global horizontal and rocking modes of the building, due to the offset of its centre of gravity above the bearings, results in two initial peaks after which the isolation is effective. The horizontal direction is rarely considered in assessing base isolation due to the argument that the building is much more flexible in this direction. However, vibration entering a building in any direction can lead to either vertical or horizontal vibration of elements within the building structure.

The results shown in Fig. 4, while more representative than those from simpler models, are still too optimistic in their prediction of isolation performance. Insertion losses of 30 dB are not experienced in practice, 10 dB is a more typical figure. In order to gain more insight into the behaviour of a base-isolated building, the various mechanisms at work must be studied separately. Consider, for example, the effect of the building on the ground vibration-field. The much simplified model shown in Fig. 5(a) consists of a SDOF rigid body, representing the base-isolated building, constructed on a rigid circular footing founded on a homogeneous isotropic linear-elastic half-space.

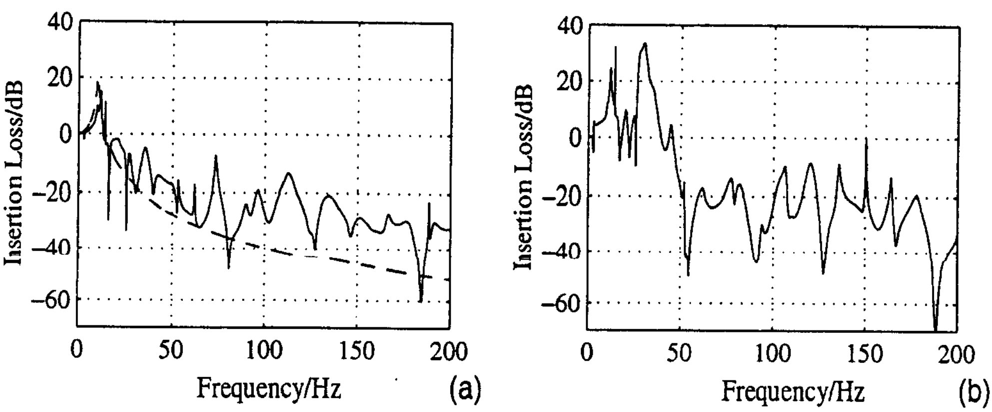

FIG. 4. Variation with frequency in the (a) vertical and (b) horizontal insertion loss of a '10 Hz' base-isolated building. The response of a rigid-body SDOF model is shown dashed for comparison.

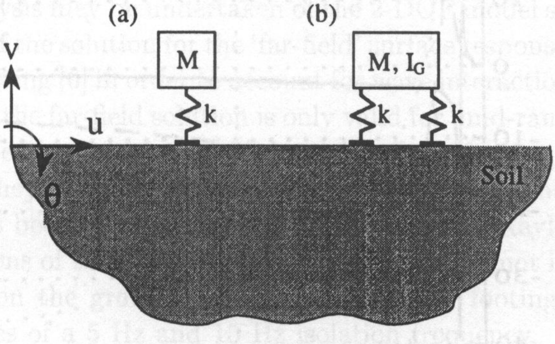

FIG. 5. Rigid-body models of a base-isolated building founded on an elastic half-space.

Assume that an arbitrary 'pre-construction' ground vibration-field exists which results in a displacement amplitude of v_0 at the site of the building. By considering the model as an assembly of two subsystems, it is straightforward to derive the 'post-construction' ground amplitude v, where H_{11} and H_{22} are the displacement frequency response functions of the half-space and SDOF system respectively:

$$\frac{v}{v_0} = \frac{H_{22}}{H_{11} + H_{22}}. \tag{3.1}$$

It is evident that for v/v_0 to approach unity (0 dB), i.e. for the construction of the building to have negligible effect on the ground vibration-field, $1/H_{11} \gg 1/H_{22}$. This is equivalent to saying that the dynamic stiffness of the ground must be much greater than that of the building.

The magnitude of Eq. (3.1) for v/v_0 is plotted against frequency in Fig. 6 for the cases of a 5 Hz and 15 Hz isolation frequency; an 'infinitely stiff' bearing is also shown for comparison. At low frequencies, two resonances dominate the behaviour of the 5 Hz and 15 Hz isolation curves; the resonance of the building on the ground occurs first, leading to amplified post-construction vibration levels, followed by the resonance of the building on the bearing, at which the high dynamic stiffness of the SDOF system constrains the ground resulting in the anti-resonances in the curves.

At high frequencies, the dynamic stiffness of the SDOF system tends towards the static stiffness of the bearing and, since this is much lower than the dynamic stiffness of the ground, the effect of the building becomes small. Note that using a lower isolation frequency affects the ground to a lesser extent, i.e. this results in higher post-construction vibration levels beneath the building. This highlights the inadequacy of simply measuring the vibration levels above and below the bearings to give an indication of isolation performance; the performance of a soft isolation may be exaggerated by higher ground amplitudes beneath it.

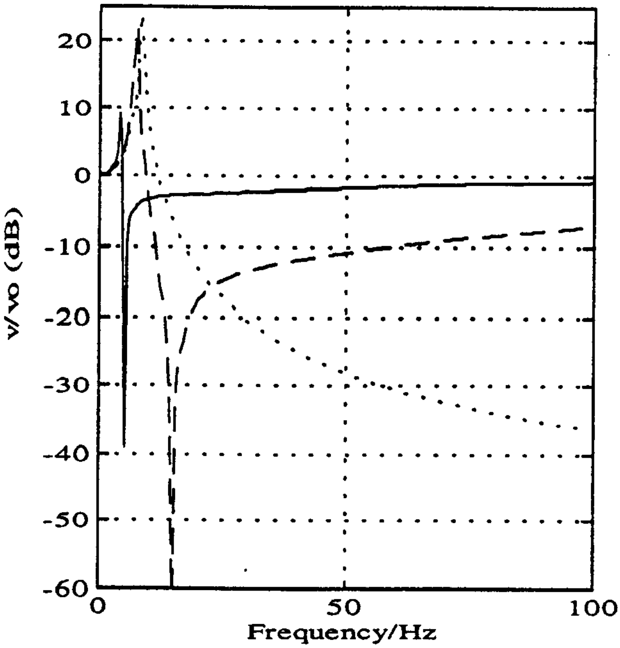

FIG. 6. The effect of a SDOF model on the ground vibration-field; (solid) 5 Hz (dashed) 15 Hz and (dotted) 'infinitely stiff' isolation.

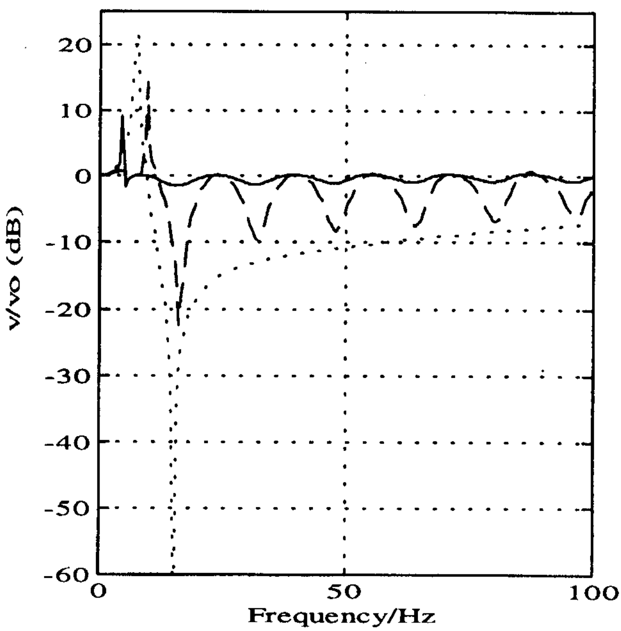

FIG. 7. The effect of a 2-DOF model on the ground vibration-field; (solid) 5 Hz and (dashed) 15 Hz isolation. 15 Hz SDOF case also shown (dotted).

A similar analysis may be undertaken of the 2-DOF model shown in Fig. 5(b). Use is now made of the solution for the 'far-field' surface response to a dynamically loaded circular footing [6] in order to account for wave interaction between the two footings. Strictly, the far-field solution is only valid for 'mid-range' frequencies; at low frequencies the wavelengths are of the order of the footing separation and at high frequencies they are of the order of the footing radius. The pre-construction vibration field has been chosen to be that due to passing Rayleigh waves and as a result, the motions of the footings, although similar, are not identical. Figure 7 shows the effect on the ground vibration-field at the footing first met by the waves for the cases of a 5 Hz and 15 Hz isolation frequency. The 15 Hz SDOF case is also shown for comparison.

As with the SDOF model, the vertical 'ground' and 'building' resonances are evident but now there are also equivalent rocking modes evident at higher frequencies (not visible in Fig. 7). Above the initial resonances, wave interactions between the two footings dominate the curves. Note that similar wave-interaction effects are present even when the pre-construction vibration-field is such that the motions at the footings are in-phase. Again, a lower isolation frequency affects the ground to a lesser extent.

4. Conclusions

This paper has discussed two alternative methods of reducing train-induced vibration in buildings, both of which can be the subject of over-optimistic predictions of performance. A detailed model of floating-slab track has been reviewed which suggests that performance predictions above 5 dB are in most cases exaggerated, and that the system may in fact provide negligible reduction, or even amplification, of vibration transmission from underground railways.

Alternative models of a base-isolated building have been presented which highlight the limitations of simpler models. Further work is required to gain more insight into the behaviour of a base-isolated building with a view to objectively evaluating isolation effectiveness.

Acknowlegments

The author gratefully acknowledges the financial assistance of the United Engineering Foundation Conference Fellowship Program. Thanks are also due to Dr Hugh Hunt, for his help and advice in the study of base-isolation, and to Dr James Forrest for the results of his work on underground railways.

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Received November 5, 1999.