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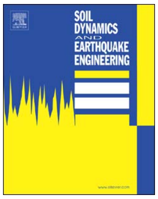

Reducing railway-induced ground-borne vibration by using open trenches and soft-filled barriers

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ABSTRACT

A trench can act as a barrier to ground vibration and is a potential mitigation measure for low frequency vibration induced by surface railways. However, to be effective at very low frequencies the depth required becomes impractical. Nevertheless, for soil with a layered structure in the top few metres, if a trench can be arranged to cut through the upper, soft layer of soil, it can be effective in reducing the most important components of vibration from the trains. This study considers the possibility of using such a realistically feasible solution. Barriers containing a soft fill material are also considered. The study uses coupled finite element / boundary element models expressed in terms of the axial wavenumber. It is found to be important to include the track in the model as this determines how the load is distributed at the soil's surface which significantly affects the insertion loss of the barrier. Calculations are presented for a range of typical layered grounds in which the depth of the upper soil layer is varied. Variations in the width and depth of the trench or barrier are also considered. The results show that, in all ground conditions considered, the notional rectangular open trench performs best. The depth is the most important parameter whereas the width has only a small influence on its performance. More practical arrangements are also considered in which the sides of the trench are angled. Barriers consisting of a soft fill material are shown to be much less effective than an open trench but still have some potential benefit. It is found that the stiffness of the barrier material and not its impedance is the most important material parameter.

1. Introduction

Ground vibration from trains is an increasingly important environmental issue. It manifests itself in two ways: low frequency vibration in the range 1–80 Hz is perceived by lineside residents as whole-body feelable vibration, whereas higher frequency vibration in the range 16–250 Hz is radiated as sound inside buildings and is known as ground-borne noise [1,2]. Trains running on surface railways, particularly where the ground is soft, often produce vibration with its highest components in the range below 40 Hz, which is mainly experienced as feelable vibration. Velocity amplitudes are typically between 0.1 and 1 mm/s. Conversely, trains running in tunnels tend to produce higher frequency vibration at considerably lower amplitudes for which ground-borne noise is more important.

Ground can often be represented as a series of parallel soil layers [1,2]. Where a shallow surface layer of softer soil overlies stiffer soil layers, the vibration is characterised by the onset of high vibration levels above a certain frequency that depends on the layer depth and wavespeeds in this upper soil layer. In many practical cases the upper layer has a thickness of 2–6 m and the corresponding cut-on frequency is typically in the range 10–30 Hz. As a result the maximum vibration often occurs in the range between 10 and 40 Hz and this must be borne in mind when considering mitigation measures [3]. At other sites where the soft soil has a greater depth and a lower wavespeed, the maximum frequency may even be lower than 10 Hz.

In principle there are a number of possible ways to reduce railway-induced vibration [1–3], including changes to the vehicle [4], modifying the track [5] or the ground beneath it [6,7] or introducing a barrier of some form beside the track. A stiff barrier in the ground beside the track, constructed for example from concrete, can give effective shielding of vibration [8–10]. It has been shown in [9] that bending waves in the stiff barrier are important.

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A row of heavy masses on the ground surface has also been shown to give attenuation of vibration at frequencies above the resonance frequency of the masses on the ground stiffness [11].

An open trench is commonly used to attenuate ground vibration from machinery [12]. This can act in a similar way to a noise barrier for airborne sound; vibration is diffracted underneath the barrier and only a fraction of the original vibration reaches the ‘shadow zone’ behind it. An ideal open trench with vertical sides is not stable so in practice it requires either sloping sides or reinforcing walls [13]. Alternatively, a trench may be filled with a soft material. This is generally less effective as vibration is transmitted through the fill material as well as being diffracted underneath the trench. The fill material should therefore be much softer than the surrounding soil while being capable of balancing the surrounding earth pressure [14]. Common fill materials considered include bentonite, soil-bentonite mixtures [15], expanded polystyrene (EPS) [16,17] and other geo-foam materials such as polyurethane [18].

Open trenches have long been considered as a possible solution for ground vibration from machinery as well as railways. Early field tests were presented by Woods [12,19]. The results were presented as the amplitude reduction ratios and a reduction of at least 0.25 (i.e. 12 dB) was considered ‘effective’. This was achieved with a trench of depth at least 0.6 times the wavelength of Rayleigh waves. The width was found not to be critical. Trenches in the far-field from the source were found to be less effective. More recently Alzawi and El Naggar [18] presented field measurements of open and soft-filled trenches. They confirmed the conclusions from Woods [12] for an open trench but found that for a trench filled with geo-foam the reductions for a depth (normalised to the Rayleigh wavelength) of 0.6 were reduced to the equivalent of about 8–10 dB. Celebi et al. [20] also presented some field measurements of a concrete-lined trench. Kim et al. [21] described an experiment with a trench filled with a mat made of rubber chips.

Massarsch [14] gave a review of the use of gas cushions. These were developed and patented by Franki International in the 1980s [22] and allow a soft-filled barrier with a very low stiffness to be used. A number of field installations to isolate buildings from railways were described. The depth varied between 6 and 12 m. He indicated, considering the transmission coefficient at the interface between two semi-infinite media, that the transmission coefficient through the barrier should depend on the ratio of the impedances of the barrier and the soil.

In [23] some trials of trenches beside both railways and tramways are reported. For example, measurements for a 3.5 m deep trench showed reductions of 10 dB above 16 Hz [23]. Yoshima [24] presented results for piled trenches adjacent to a high speed line. At one site the trench was 4 m deep and at another it was 10 m deep; the frequency-weighted vibration was reduced by around 10 dB. Lang [25] found that a 1.5 m deep trench filled with railway ballast reduced vibration from a tram line by around 10 dB above 31.5 Hz, although the benefit decreased at larger distances. François et al. [26] described an installation of an 8 m deep screen consisting of polystyrene, concrete and bentonite alongside a tram track. The results obtained were disappointing, this being attributed to an insufficient stiffness ratio between the barrier and the surrounding soil. Although various results have been cited, published measurement results for track-side trenches are scarce and they are difficult to generalise. The vibration reduction will depend strongly on the ground conditions as well as on track and vehicle design. Numerical analysis can provide an alternative which allows a more systematic understanding to be developed.

The main approaches used to model soil-structure interaction [27] are the boundary element (BE) method and the finite element (FE) method. To prevent reflections at artificial boundaries of the model, the FE approach is often used together with the BE method or with infinite elements (IE) or other non-reflecting boundaries.

May and Bolt [28] used two-dimensional (2D) FE models to study the effect of an open trench on incident waves of different types. They confirmed that a non-dimensional depth of 0.6 is sufficient to obtain a reduction of 12 dB. Beskos et al. [29–31] introduced 2D and 3D BE models of open trenches. Their results confirmed that a non-dimensional depth of at least 0.6 is required to give an amplitude reduction of 0.25 (12 dB). Ahmad and Al-Hussaini [32] also used 2D BE models to study an open trench, extended to 3D in [15]. Klein et al. [33] used a 3D BE method to study an open trench and Kattis et al. [34] studied a row of piles. Ekanayake et al. [17] used an FE model to study an open trench and one filled with expanded polystyrene (EPS) geofoam or water.

Most published results are based on a homogeneous ground. May and Bolt [28] included a surface layer but the wavespeeds differed only by 20%. Leung et al. [31,35] considered a layered or continuously non-homogeneous ground. They found that, for a softer layer over a stiffer half-space, the effectiveness of a trench is significantly reduced compared with a homogeneous material. A depth of twice the Rayleigh wavelength was found to be necessary where the upper layer was shallower than 2.5 wavelengths [31]. Ahmad and Al-Hussaini [32] also gave results for an open trench in a layered half-space, with similar conclusions.

The numerical modelling of trenches has been extended to study the effect on railway vibration by a number of authors. Yang and Hung [36] used 2D FE/IE models of an open trench and found that a high Poisson's ratio of the soil meant that an open trench had to be deeper for the same effectiveness. Hubert et al. [37] used 3D BEM in the time domain to study a rigid track on a half-space and the introduction of an open trench. Results were given only for two example frequencies. Adam and von Estorff [38] used a 2D coupled FE/BE model to study the transmission of vibration from a railway to a nearby building. Both an open trench and a trench filled with soil-bentonite mixture were considered. A 3D FE/BE model which operates in the frame of reference moving with the load was presented by Andersen and Nielsen [39]. An open trench and a trench filled with rubber chips were considered as well as other options.

Connolly et al. [40] used a 3D FE model to study the effects of an open trench adjacent to a railway line. It was shown that the depth is important but the width is not. Results were shown in terms of non-dimensional parameters expressed in terms of a single equivalent frequency representing the train pass-by loading. A 3D FE model was also used by Younesian and Sadri [41] to study trenches with different cross-sections.

Hung et al. [42] used a 2.5D FE/IE approach to study an open trench and a concrete-filled trench. In such an approach, the mesh is two-dimensional and the third dimension is represented in the wavenumber domain. Barbosa et al. [43] presented results from a full 2.5D BE/FE model of the track and ground including a moving excitation. Results were given for an open trench, a trench filled with geo-foam and a concrete barrier. They found that it is important to include the moving load on the track, especially for the stiff barrier.

From both measurements and computer modelling of railway vibration, it has been found that the most important frequency components are controlled by vibration propagation in upper layers of soil that are often only a few metres deep [1]. This suggests that a trench that cuts through such a surface layer may have the potential to give significant reductions of the most important parts of the vibration spectrum. Jones et al. [13] used a two-dimensional boundary element model to study rectangular trenches in a layered ground, considering the effect of their depth and position. The ground consisted of a 2 m layer of alluvial soil over a substratum of stiffer material (say, gravel beds). This study was extended in [44] to include trenches with a retaining structure or a