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Mitigation of railway-induced vibration by using subgrade stiffening

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ABSTRACT

Railway-induced ground vibration is often associated with sites with soft ground. Stiffening of the subgrade beneath the railway track is one particular measure that has potential to reduce the vibration level at such sites. However, the mechanisms behind this reduction are not well understood. Here, the effects are examined in the context of two alternative approaches: (i) subgrade stiffening, where the soil directly under the track is stiffened, and (ii) stiff inclusions introduced at some depth beneath the track, sometimes known as 'wave impeding blocks'. The efficacy of the measures is considered for different ground types in a parametric study carried out using a 2.5D coupled finite-element/boundary-element methodology. The soil is considered to consist of a soft upper layer over a stiffer substratum; corresponding homogeneous grounds are also considered. With a 6 m wide, 1 m thick, concrete block directly under the track, the vibration between 16 and 50 Hz was found to be reduced by between 4 and 10 dB for ground with a 3 m deep soft upper layer. For a deeper soft layer the reductions were greater whereas, for a stiffer ground without the soft upper layer, the reductions in vibration from this block were negligible. Slightly smaller reductions in a similar frequency region were observed when the block was positioned 1 m below the surface, suggesting that, as with stiffening directly under the track, the reduction in vibration was primarily due to the increase of the effective stiffness of the soil beneath the track rather than the effective creation of a new, thinner soil layer. Jet grouting is considered as an alternative to concrete and, although it is found to be less effective due to its comparatively low stiffness, it may still be considered as a practical measure for existing tracks on soft soil sites. The reduction in vibration from this form of soil improvement with a depth of 3 m is similar to that for a 1 m thick concrete block. Finally, results are presented for three example sites with different soil properties which show similar trends.

1. Introduction

Ground-borne vibration is a commonly reported problem for residents of buildings near railway lines. Vibration is generated at the wheel/rail interface due to various mechanisms, including track unevenness, the effect of quasi-static moving loads, and transient effects due to rail joints, switches and crossings [1,2]. Typically, ground-borne vibration is perceived as feelable whole-body vibration in the frequency range 1–80 Hz and as ground-borne noise in the frequency range 16–250 Hz. Vibration at higher frequencies is generally attenuated more rapidly with distance along the transmission path through the ground [3]. Feelable vibration is often associated with surface railways whereas ground-borne noise is more commonly associated with trains in tunnels. In addition to annoyance of building occupants, low frequency vibration can also cause malfunction of sensitive equipment [4].

In general, ground-borne vibration from trains can be attenuated by introducing control measures at the source or at the receiver or by interrupting the transmission path [5]. Vibration can be attenuated at the source [6–8], for example, by using soft rail fasteners, resiliently-mounted sleepers, under-ballast mats or floating slab tracks. However, for surface railways the benefit of such measures is usually limited to higher frequencies that are of less relevance to feelable vibration. The frequency range where vibration isolation can be achieved depends on the track mass and the stiffness of the resilient elements. Apart from floating slab track, vibration isolation by such track forms is only achieved at frequencies typically above 30–50 Hz [2]. Control at the source can also be achieved by enhancing the track foundation stiffness, which is the technique considered here.

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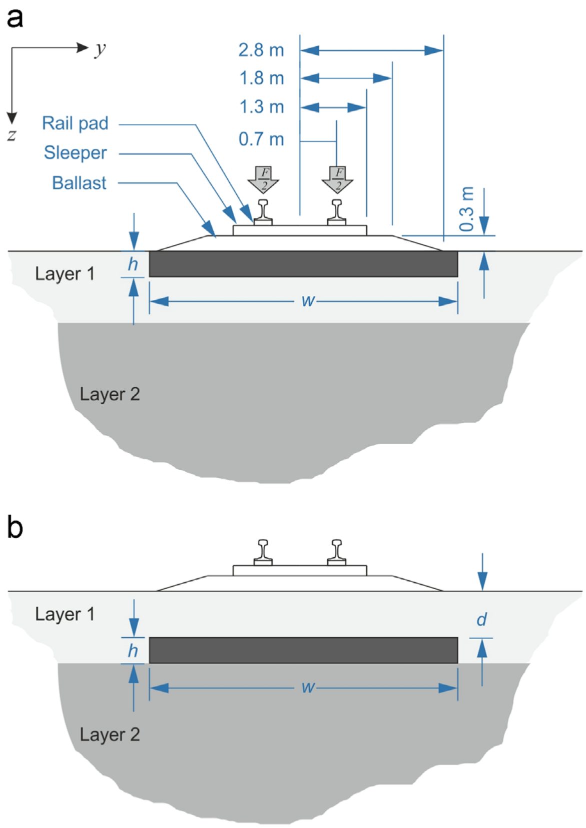

Fig. 1. Example sketch of track section at layered soil site with soil stiffening (a) at the surface and (b) at a certain depth.

Vibration can be attenuated at a building by introducing resilient elements between the building and its foundation, a technique known as base isolation [9]. A reduction of vibration can also be achieved for a particular part of the building, e.g. by isolating a floor or a whole room [10]. The choice between measures applied at the source or at the receiver depends, for example, on whether a new building is to be constructed near an existing railway or a new or renewed railway is to be built close to existing buildings. Finally, attenuation in the transmission path can be achieved, for example, by using open trenches [11], in-filled trenches [12], rows of piles [13] or heavy masses [14]; each of these may be located close to the track or close to the buildings to be protected.

The work presented in this paper explores the effects of subgrade stiffening on ground-borne vibration from surface railways. The arrangements considered are shown schematically in Fig. 1. Stiffening of the subgrade beneath the railway track is often applied at sites with soft soil to reduce track settlement and track deflections but it has also been associated with a potential reduction in ground-borne vibration [15–18]. Various techniques can be applied to achieve the desired subgrade stiffening, e.g. vibro-compaction, vibro-replacement, jet grouting or excavation and replacement by a new material such as concrete. It is of note that the method offers the prospect of vibration reduction at very low frequencies, in contrast to track isolation which is effective only at higher frequencies.

Few practical tests have been reported, but where experimental results exist they appear promising. At the unusually soft soil site of Ledsgård in Sweden, when the train speed exceeded the speed of Rayleigh waves in the upper soil layers, very high levels of vibration occurred below 10 Hz [19]. Lime cement columns installed beneath the track were successful in alleviating the situation [20]. However, it should be noted that there are no buildings in the vicinity of the track and the main concern was to stabilize the track rather than to reduce environmental vibration. At a soft soil site at Rainham Marshes in England, concrete bridge decks supported on piles have been used to prevent excessive motion of the track [21].

A variant of subgrade stiffening directly beneath the track is to stiffen the soil at some depth beneath the track, see Fig. 1. In the literature this has been referred to as a wave impeding block [16,17]. It is thought that vibration is reduced in this case because the stiffened block behaves like a rigid layer [22], in which case, wave propagation would only occur in the (softer) soil layer above it for frequencies higher than the cut-on frequency of waves in this constrained layer. As such, the block should ideally be infinitely wide and stiff. The effect of a more 'practical' 12 m wide, 0.6 m thick concrete block positioned at a depth of 1.4 m was considered in [22] using a coupled wavenumber finite element-boundary element (so-called 2.5D FE/BE) approach [23]. The upper soil layer in this analysis was initially 2 m deep and very soft. Below this layer was a much stiffer half-space. The results of the study were promising; the block provided more than 10 dB vibration reduction for all frequencies between 10 and 50 Hz.

For practical implementation, distinction should be made between installation as part of new track construction and retrofitting of existing tracks. For new tracks it may be possible to include subgrade stiffening as part of the construction so here a wide range of materials could be considered. However, for retrofitting of existing tracks, soil improvement techniques such as jet grouting should be considered. Moreover it may be required to install this at some depth beneath the track to avoid affecting the track geometry.

Promising results have been found from previous computational analyses of subgrade stiffening, either directly below the track or at a depth. However, for the limited number of cases considered so far it is not clear to what extent the parameters relating to the stiffened subgrade (e.g. geometry and material properties) and the soil (e.g. layering, material properties) influence the performance of the measures. In this paper a systematic investigation is presented of the effect of subgrade stiffening on ground vibration from a surface railway with particular emphasis on the influence of the soil layering. Stiffening of the subgrade both directly beneath the track and at a depth are considered, see Fig. 1. Initially, a set of site conditions is considered in which a soft soil layer overlies a stiffer substratum. By varying the depth of the upper soil layer, the effect of this stratification is seen on the vibration due to a train passage and on the effect of introducing subgrade stiffening in various configurations. In the final section, results are presented for three example sites with differing ground properties to show the likely effects of subgrade stiffening at these sites. Note that, in all the cases considered, the train speed is much less than the ground wave speeds, so the effect studied is the reduction of environmental ground vibration [1], not the mitigation of critical velocity effects [19,20].

2. Models

2.1. 2.5D finite element/boundary element approach

To model ground vibration in unbounded domains it is important that propagating waves are correctly modelled. Finite element (FE) approaches therefore require absorbing boundaries to prevent reflections from the edges of the domain [24]. An alternative is to use boundary element (BE) methods which intrinsically account for the infinite domain. These can be coupled with finite element models of the track and local structures [25].

The geometry of a railway line with the measures described here is two-dimensional but the response field due to the loading