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Efficacy of a sheet pile wall as a wave barrier for railway induced ground vibration

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ABSTRACT

This paper investigates the effectiveness of a sheet pile wall to reduce railway induced vibration transmission by means of field measurements and numerical simulations. At Furet, Sweden, a sheet pile wall has been installed in the soil near the track to reduce train induced vibrations in houses close to the track. The depth of the sheet piles is 12 m with every fourth pile extended to 18 m. The efficacy of the wall is determined from in situ measurements of free field vibrations during train passages before and after installation of the sheet pile wall. The field test shows that the sheet pile wall reduces vibrations from 4 Hz upwards. Up till 16–20 Hz, the performance generally increases with frequency and typically decreases with increasing distance behind the wall. The performance is further studied by means of two-and-a-half-dimensional coupled finite element–boundary element models. The sheet pile wall is modelled as an orthotropic plate using finite elements, while the soil is modelled as a layered halfspace using boundary elements. The sheet pile wall acts as a stiff wave barrier and the efficacy is determined by the depth and the stiffness contrast with soil. The reduction of vibration levels is entirely due to the relatively high axial stiffness and plate bending stiffness with respect to the horizontal axis of the sheet pile wall; the plate bending stiffness with respect to the vertical axis is too low to affect the transmission of vibrations. Therefore, it is important to take into account the orthotropic behaviour of the sheet pile wall. It is concluded that a sheet pile wall can effectively act as a wave barrier in soft soil conditions provided that the wall is sufficiently deep.

1. Introduction

Railway induced ground vibration can be a source of annoyance for lineside residents. Vibration in buildings ($1-80$ Hz) may cause malfunctioning of sensitive equipment and lead to discomfort of inhabitants. The vibrating walls and floors also radiate low frequency noise in the frequency range 16–250 Hz. In case of excessive vibration levels, mitigation measures can be taken at the source, on the transmission path, or at the building where vibration problems occur [1,2]. In general, the mitigation of low frequency feelable vibration which involves surface waves with longer wavelengths and larger penetration depths is far more difficult [3] than the mitigation of high frequency ground vibration leading to ground-borne noise. Many of the mitigation measures at source, like soft railpads [4] and under-sleeper pads [5], will mainly lead to a reduction in the frequency range of relevance to ground-borne noise. Initial numerical analysis and preliminary experiments show that mitigation measures on the transmission path offer the prospect of obtaining vibration reduction at low frequencies [3]. In addition, interventions on the propagation path between source and receiver have the advantage that no modifications of the track are required. These measures include open and in-filled trenches [6,7], wave impeding blocks [8,9] and heavy masses on the soil's surface [1,10,11].

The efficacy of both open and in-filled trenches has been studied by means of analytical models [12], finite element (FE) models [13], boundary element (BE) models [14,15] and coupled FE-BE models [8,16]. In the case of a homogeneous halfspace, an open trench proves effective when the depth is at least 0.6 times the Rayleigh wavelength in the soil [6,17]. The location and width of the trench are of secondary importance [17]. The isolation effectiveness typically decreases with distance, as wave diffraction can occur around the bottom of the trench [7,18]. The presence of shallow soft soil layers, often only about 2 m deep, leads to increased vibration propagation at frequencies where surface waves can propagate predominantly in these layers [18]. In this case, an open trench can already be effective when the trench cuts

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through the upper layers [19,20]. The practical application of vertical open trenches is limited to shallow depths, however, for stability reasons and the presence of groundwater. More practical realisations of trenches with sloping sides or a retaining structure have been investigated as well [18,21]. These studies indicate that the retaining structure can significantly reduce the efficacy.

To increase the depth and improve durability, trenches with soft or stiff in-fill materials can be used as a wave barrier. In general, in-filled trenches are less effective than open trenches [8,16,17,20]. While the efficacy of open trenches is mainly determined by their depth, the ratio between the bending stiffness of the barrier and the soil proves crucial for stiff wave barriers [6,7,22–24]. Therefore, stiff wave barriers are mostly effective at soft soil sites. For trenches filled with a soft material, the vibration isolation efficiency is mainly determined by their depth and the stiffness contrast between barrier and soil [20,25]. The vibration isolation is improved by increasing the width of the barrier or decreasing Young's modulus of the soft in-fill material [20,26].

Most numerical studies are based on two-dimensional (2D) or two-and-a-half-dimensional (2.5D) analysis assuming a barrier of infinite length. Three-dimensional (3D) analysis has also been used to investigate the influence of the finite length of open trenches and concrete barriers [27]. Coulier et al. [28] showed that diffraction effects occur around the edges of an open trench or stiff wave barrier with finite length, with a limited effect for a source at a fixed, central location. Full 3D models have also been used to study the effect of a row of piles with different separation distances [29–31]. Kattis et al. [32] presented an equivalent isotropic wave barrier model for a row of circular or square piles.

Although numerous numerical studies of open trenches and wave barriers have been reported, the number of full scale experiments is small. First experimental results on open trenches have been reported by Woods [33], Dolling [34] and Richart et al. [35]. These tests confirmed that an open trench starts to be effective if the depth is large enough compared to the Rayleigh wavelength. Klein et al. [15] performed tests on a 2 m deep trench with sloping sides, showing that the influence of the distance between source and trench is small. More recently, Alzawi et al. [36] presented full scale tests of a 20 m deep and 3 m wide open trench where a harmonic shaker was used as a vibration source. Afterwards, the trench was filled with geofoam, showing an overall reduction in effectiveness of 50%. Other realisations of soft wave barriers include screens made of inflated gas cushions [37,38], rubber chip barriers [39], and PUR sandwich panels [40]. The obtained reduction in practice is generally less than predicted, but well-designed barriers can approach the theoretical effectiveness of an open trench [38]. Vibration reduction measurements for an 8 m deep composite vibration screen, consisting of an expanded polysyrene core and concrete side panels, installed near a tramway in Belgium, showed a limited performance [25]. Scale model tests on concrete barriers have been performed by Haupt [23]. Çelebi et al. [41] compared the vibration isolation of a 3 m long and 2.5 m deep concrete filled trench with that of an open trench, a water filled trench, and a bentonite filled trench. It was found in these studies that concrete barriers, like soft wave barriers, can reduce vibrations but are less effective than open trenches. Full scale tests of stiff wave barriers include the study of four rows of 12 m deep lime-cement columns installed next to a track in Sweden [42]. Within the frame of the EU FP7 project RIVAS (Railway Induced Vibration Abatement Solutions) [44], a 55 m long and 7.5 m deep jet grouting wall was installed next to a track on a test site in Spain [43]. Both tests proved successful with a significant reduction of vibration already at low frequencies, but the performance decreases further away from the barriers.

In this paper, the vibration isolation efficiency of a sheet pile wall is investigated. At Furet, Sweden, a sheet pile wall with a length of 100 m has been installed next to the track [45,46] in order to reduce train induced vibrations in several buildings close to the railway track. The sheet pile wall designed and constructed by Trafikverket was subjected to experimental and theoretical analysis within the frame of the RIVAS project [44]. The results of this analysis are presented in this paper. Whereas a large number of papers either focusses on numerical predictions of mitigation effectiveness or on technical construction aspects, the effectiveness of the sheet pile wall in Furet is investigated both with state-of-the-art 2.5D numerical predictions and in situ testing.

The outline of the paper is as follows. Section 2 introduces the test site in Sweden and addresses the determination of the dynamic soil characteristics. The sheet pile wall design and installation is discussed in Section 3. The results of the measurement campaign are subsequently presented in Section 4. The experimental results are compared to results obtained by coupled FE–BE simulations in Section 5. Additional simulations are performed for the case of a homogeneous halfspace for better understanding of the wave impeding effects and for the case of an isotropic wall to study the influence of orthotropy. Conclusions are drawn in Section 6.

2. Site description and characterisation

The site of Furet (Fig. 1) is located in the southwest of Sweden in the city of Halmstad, 700 m north of Halmstad station, along the West Coast Line between Göteborg and Lund. The wooden buildings in Furet have two to three floors and were mostly built around 1950 at the north-west side of the track along a distance of 750 m. The track is a classical ballasted track.

In 2002 a court decision stated that vibrations inside the buildings must be less than 1.0 mm/s frequency weighted RMS at night (10 pm to 7 am). Measurements according to the Swedish Standard SS 460 48 61 [47] indicated that this threshold was exceeded in at least ten buildings in the south part of Furet with values ranging from 1.3 to 2.0 mm/s frequency weighted RMS. The dominating frequency component of the indoor vibration was typically between 4 and 5 Hz.

A first attempt to mitigate vibrations was undertaken in 2006. New sleepers with under sleeper pads were placed at the track closest to the buildings. At the same time, levelling of the track was carried out. These mitigation measures did not lead to a significant reduction of vibration levels in the houses. To further reduce the train induced vibrations at the site, a sheet pile wall was installed next to the track in 2011. Measurements after installation of the sheet pile wall showed sufficient reduction of vibration levels, except for a small three storey house with wooden structure at approximately 40 m from the track.

Geotechnical and geophysical tests have been carried out for the determination of the soil layering and the dynamic soil characteristics at the test site. Surveys, performed by the consulting company Tyréns in March and April 2011 at 4 locations in the area up to a depth of at least 18 m, include cone penetration tests (CPT), seismic cone penetration tests (SCPT), standard piston sampling, sampling by Helical auger and weight sounding. The soil profile consists of a relatively firm layer of sand up to 2–3 m depth underlain by clayey silt up to a depth of 5–10 m, underlain by silty clay. The silt has a density of 1850 kg/m^3 and the clay a density of 1710 kg/m^3. These densities are determined as average values from three samples per meter from one borehole. The CPT tests indicate an undrained shear strength of 20–35 kPa up to 13 m depth and an undrained shear strength of 50–70 kPa at larger depths.

The shear wave velocity C_s was determined by means of a multichannel analysis of surface waves (MASW) and SCPT test