Simulating ground vibration from underground railways through subsiding soil layers

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*Keywords*: underground railway, thin-layer method, vibration, subsidence, soil

Underground railways can efficiently transport large numbers of people in densely populated areas; however, studies show that individuals subjected to noise and vibration from rail traffic report high levels of annoyance and sleep disturbance (Fidell et al., 1991; Miedema and Vos, 1998). The frequency range of interest is between 5Hz and 200Hz as listed in BS 6472:1992 and BS ISO 14837 Part 1. Predictive models should focus on the problem frequency range between 15Hz and 150Hz; higher frequencies are attenuated by the soil through geometric decay and material damping, while lower frequencies are weakly excited and generally below the threshold of human perception (Greer and Manning, 1998).

Designers of underground railways and surrounding buildings can use vibration predictions to allow for efficient and economical planning of vibration countermeasures; finite element (FE) and boundary element (BE) methods are commonly employed for such simulations. Although FE/BE permit accurate modelling of complex geometrical regions (e.g. square tunnels, piled foundations, buildings, etc.) these models can require tens of hours to compute the response at a single loading frequency making in-depth parametric design-studies intractable. In the early design stage designers are often interested in determining which parameters have the most significant effect on ground vibration rather than simulating fully coupled tunnel-soil-building response. A more economical approach to simulating ground vibration due to underground railways involves semi-analytical methods. The current paper further develops the authors’ model (Jones and Hunt, 2008; 2009) to investigate the effect of soil subsidence over the tunnels on ground vibration.

Ground movement associated with the construction of underground railway tunnels is inevitable. As the tunnelling face progresses forward the lack of support for the overburden causes the ground above the tunnel to sag. This subsidence trough can be described by a Gaussian error function as described mathematically below (Peck, 1969; O’Reilly and New, 1982)

\[
f(x) = S_0 e^{-\frac{(x-x_0)^2}{2\sigma^2}}
\]

\[
S_0 = \frac{1.25V_L}{0.175 + 0.325 \left(1 - \frac{x}{x_0}\right)^2} R^2
\]

Figure 1: Schematic showing the Gaussian nature of a subsidence trough over an underground railway tunnel
where \( x \) and \( z \) describe the location of interest for the subsidence estimation, \( x_0 \) and \( z_0 \) are the location of the centreline of the tunnel, \( V_L \) is the volume loss per unit length, and \( R \) is the radius of the tunnel being excavated. Current studies using space radar interferometric techniques show subsidence levels of \( S_{v,max} = 10-20 \text{ mm/year} \) (\( V_L = 3-9\% \)) for underground railways in the UK, Korea, Chile and Greece (Knight, 2002; Kim et al., 2007; Parcharidis, 2006). The yearly subsidence over the tunnels is attributed to water leakage into the tunnels resulting in a loss of pore pressure in the surrounding soil. It is conceivable that a subsidence trough of 40-50mm could develop over an underground railway tunnel during its lifetime. The goal of the current paper is to quantify the effect such subsidence would have on surface vibrations.

The model presented herein is an extension of the previous model used by Jones and Hunt (2008; 2009) which employs plane-strain semi-analytical elements (i.e. hyperelements, semi-infinite elements, and halfspace elements) to predict ground vibration. The elements utilize the analytical solution for horizontal wave propagation while assuming vertical displacements vary linearly through the thickness of the element. Doing so allows the governing equations of motion for a solid to be written in eigenvalue form and solved in modal coordinates. The stiffness matrix for each thin-layer can be coupled together using standard finite-element addition techniques to produce the total stiffness matrix for a subsiding, layered halfspace which is computationally efficient to solve.

The plane-strain case presented in this paper consists of an upper layer resting on a halfspace, a buried tunnel, and an area of subsidence over the tunnel. A white-noise harmonic line-load is applied to the bottom of the tunnel invert for frequencies ranging between 10Hz to 150Hz with 5Hz steps and the rms particle velocity at the surface is calculated using standard random vibration theory (Newland, 1984). The elastic modulus of the upper layer is varied to investigate the effect of a layer with faster and slower wave speeds than the halfspace. The subsidence is varied between \( S_{v,max} = 0 \) and 67mm and the results are compared to determine the effect of subsidence on surface vibration.

The results from the model show only a small difference in surface rms velocity predicted between the model with subsiding layers versus horizontal layers (+/- 1.5 dB rms, ref 1 m/s); this suggests that neglecting to account for subsidence when simulating ground vibrations from underground railways will not add a significant amount of uncertainty to the predicted levels. The semi-analytical simulation took an average of 11 seconds per frequency step to calculate the surface rms velocity. In comparison, a boundary element model of similar complexity used in a previous verification model (Jones and Hunt, 2009) took on average 8 minutes per frequency step.

References


