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# 2.5D vibration of railway-side buildings mitigated by open or infilled trenches considering rail irregularity

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## ABSTRACT

A 2.5D analysis is presented of the vibration reduction of buildings alongside the railway by open or infilled trenches. Assuming the soil-structure system to be uniform along the railway direction, the 2D profile is used for obtaining the 3D response of the system by the 2.5D approach. Unlike most previous studies, the effect of self oscillation frequencies of the train due to wheel-rail interaction associated with rail irregularity is duly taken into account, in addition to the train and trench parameters. Focus is placed on the difference between the 2D and 2.5D results and on the mechanism of isolation of for the building. Contrary to the 2D analysis, the 2.5D response for the floor is found to be higher than the ceiling, implying that the wave transmission effect along the railway direction is greater than the amplification effect of the building structure. In addition, the 2.5D results are generally smaller than the 2D ones due to confinement of energy on the 2D plane. Both open and in-filled trenches are good for reducing building vibrations induced by trains, especially by those with higher self-oscillation frequencies when moving over irregular railways.

## 1. Introduction

With the advancement of modern technology, more and more rail transit systems have been built to relieve traffic congestion in densely populated cities. It is inevitable that railway lines may pass through residential or vibration-sensitive areas where high-precision labs or factories are located. For this, train-induced vibrations on soils and buildings, and methods of isolation have attracted the attention of a growing number of researchers in both the academic and engineering sectors.

Researches on train-induced vibrations of soils and relevant isolation means can be classified by three categories. The first category can be referred to as *active isolation*, which is aimed at reducing the vibrations emitting from the source, including the vehicle model, train speed and track system. The effect of floating slab tracks on the train-induced vibrations was studied by Grootenhuis [1], Wilson et al. [2], and Balendra et al. [3]. They concluded that the floating slab track has a significant effect on reducing the vibrations above the natural frequency of the floating slab. Krylov [4] studied theoretically the ground vibrations induced by superfast trains, considering the contribution of sleepers of the track. He concluded that larger amplitudes of vibration will be induced when train speed exceeds the Rayleigh waves velocity, along with some mitigation measures based on waveguide effects for ground vibrations. Heckl et al. [5] showed that in order to avoid excessive vibrations induced, the train speed should not be too high, the track and wheels should be smooth, and the support structure should be stiff enough and as homogeneous as possible.

The second category can be referred to as the *passive isolation*, which hinges on protection of the target structure from external excitations. Talbot and Hunt [6] proposed a computationally efficient piled-foundation model for studying the effects of ground-borne vibration on buildings. Using the 3D finite element approach, Ju [7] studied the isolation effect of different foundations, i.e. retaining walls, improved soil conditions and pile foundations, on the building vibration induced by trains moving over bridges. Fiala et al. [8] studied the structural and acoustic response of a building to high-speed surface railway traffic, considering three different vibration countermeasures: floating-floor, room-in-room, and base-isolation. François et al. [9] studied the isolation performance of three types of foundations, i.e., slab, strip and box foundations, on the dynamic response of buildings to traffic induced wave fields. Auersch [10] studied the effect of wave propagation of the half-space with an interior source on buildings supported by piles or pile groups.

The last category is on the application of various *wave barriers*, such as open and in-filled trenches [11–22], pile wave barriers [23,24] and wave impeding blocks (WIBs) [25], for reducing the train-induced vibrations. Woods [11] studied the performance of trenches on reducing the vibrations of soils by field model tests. Beskos and co-workers

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studied the vibration isolation of homogeneous soils, layered soils and non-homogeneous soils by trenches using the 2D and 3D finite and boundary element methods [12–16]. Similar problems were studied by Ahmad and co-workers [17,18]. Using the 2D finite/infinite element method, Yang and co-workers conducted a parametric study on wave barriers for reduction of soil vibrations induced by trains [19]. They also proceeded to study the effect of wave barriers in mitigating train-induced vibrations on adjacent buildings [20]. Adam and von Estorff [21] analyzed the effectiveness of trenches in reducing the train-induced vibrations on buildings considering the 2D soil-structure interaction. Alzawi and El Naggar [22] conducted a full scale experimental study on the protective performance of open and in-filled trenches with GeoFoam materials. Using the frequency domain boundary element method, the problem of vibration isolation of soils by a row of piles was studied by Kattis et al. [23,24].

All the papers cited above have used either the 2D approach [3,12–14,17,19,20,25] or 3D approach [6–9,15]. The advantage of the 2D approach is simplicity, which is good for qualitative assessment in initial design. But it fails to simulate the wave propagation along the railway direction for different train speeds. It is true that the 3D approach can overcome the deficiencies of the 2D approach, in that the wave propagation along the railway direction is taken into account. However, a realistic 3D soil-structure analysis is extremely time-consuming and computationally prohibitive in practice.

The 2.5D approach devised by Yang and Hung [26] in 2001 is aimed at alleviating the drawbacks of the 2D and 3D approaches mentioned above. By this approach, a soil-structure system is assumed to be *uniform* along the railway direction. A 2D profile equipped with both *in-plane* and *out-of-plane displacements* can be used to simulate the 3D wave propagation behavior of the system. In the literature, concepts similar to the 2.5D approach have been adopted by researchers to study various soil vibration problems. For instance, Sheng et al. [27] adopted the same assumption of homogeneity for the soil-tunnel system in the track direction in their analysis. Degrande et al. [28] assumed the geometry of the half space to be periodic in the tunnel direction, and adopted the Floquet transform in their soil-tunnel analysis for moving trains. Müller et al. [29] assumed the structure to be invariant in the longitudinal direction of the tunnel, and analyzed the behavior of a plate elastically mounted on the tunnel due to a moving vehicle.

The 2.5D finite/infinite element approach devised by Yang and co-workers is an extension of their early works for 2D problems [19,20,30–32]. The infinite element has been used to simulate the infinite domain of the half-space for its compatibility with existing finite element codes and for its easiness in dealing with radiation damping due to geometric attenuation [30].

Using the 2.5D finite/infinite element approach, Hung et al. [33] studied the performance of different wave barriers in reducing the soil vibrations induced by trains. The rail roughness was first included by Hung et al. [34] in their 2.5D soil responses induced by moving trains. Yang et al. [35] compared the train-induced soil vibrations obtained by the 2D and 2.5D finite/infinite element approaches. Recently, Liang et al. [36] presented an efficient and accurate algorithm for simulating the effect of moving train loads on soil vibrations by the 2.5D approach.

From the above review, it is clear that the 2.5D approach has not been employed to study the vibration reduction of *buildings* alongside the railways using open and infilled trenches. Moreover, the effect of *rail roughness* that is crucial to the building responses was *not* well documented. The purpose of this study is to fill such a gap. In the 2.5D analysis, focus will be placed on the physical interpretation of the mechanism of isolation offered by the wave barriers on the vibration of buildings alongside the railway. The performance of isolation will be discussed in terms of velocity, acceleration and displacement for various ranges of frequencies.

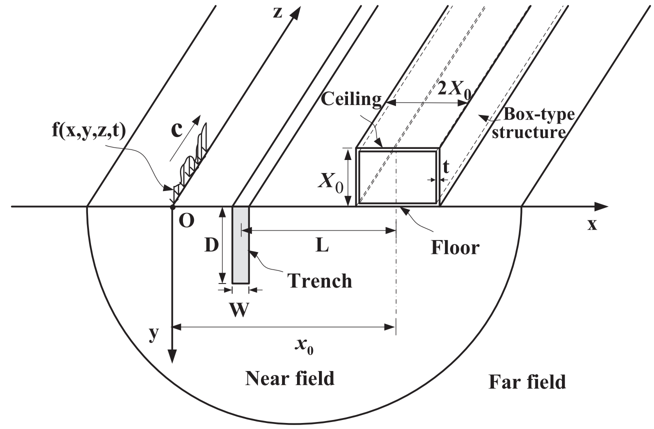


**Fig. 1.** Soil-structure model.

## 2. Formulation and basic assumptions

For the present purposes, let us consider a train load moving at speed $c$ on the soil surface along the $z$-axis (Fig. 1), which can be expressed as follows [26]:

$$f(x, y, z, t) = \psi(x, y)\phi(z - ct)R(t) \tag{1}$$

Here $R(t)$ denotes the wheel-rail interaction force, which for simplicity is taken to be a harmonic function $T\exp(i\omega_0 t)$ with self-oscillation frequency $\omega_0 = 2\pi f_0$ and amplitude $T$ (i.e. the train weight). For $\omega_0 = 0$, $R(t)$ reduces to a quasi-static wheel load with no oscillation. For $\omega_0 \neq 0$, $R(t)$ represents the dynamic oscillation of the train load caused by rail roughness and wheels defects. A more general expression of $R(t)$, consisting of a *quasi-static term* for the train weight and a *dynamic term* for the oscillation due to rail roughness, will be detailed in Section 4.6 when dealing with irregular rails later on. In Eq. (1), $\psi(x, y)$ is the load distribution on the $(x, y)$ plane, which for simplicity is taken as $\psi(x, y) = \delta(x)\delta(y)$ in Fig. 1, where δ is the delta function, and $\phi(z)$ is the load distribution along the $z$-axis. By the Fourier transformation, the train load can be expressed as

$$\tilde{\tilde{f}}(x, y, k_z, \omega) = \psi(x, y)\tilde{\phi}(k_z)\tilde{R}(k_z c + \omega) \tag{2}$$

where $\tilde{\phi}(k_z)$ and $\tilde{R}(k_z c + \omega)$ respectively denote the Fourier transforms of $\phi(z)$ and $R(t)$ with respect to $z$ and $t$. Inversely, the train load can be recovered as

$$f(x, y, z, t) = \psi(x, y)\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{\phi}(k_z)\tilde{R}(k_z c + \omega)\exp(ik_z z)\exp(i\omega t)dk_z d\omega \tag{3}$$

Thus, the steady-state response of the half space, a linear system, can be computed by summing up the response caused by each of the harmonic functions constituting the train load. With the *frequency response function* (FRF) $H(k_z, \omega)$ computed for the half space for each harmonic function $\psi(x, y)\exp(ik_z z)\exp(i\omega t)$, say, by the 2.5D approach to be briefed later on, the total response of the system is

$$d(x', y', z, t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\tilde{\phi}(k_z)\tilde{R}(k_z c + \omega)H(k_z, \omega)\exp(ik_z z)\exp(i\omega t)\,dk_z d\omega \tag{4}$$

To derive the train load function $f(x, y, z, t)$, one may consider for instance the train model with $N$ cars in Fig. 2, where $L_{t0}$ denotes the distance from the observation point to the 1st wheelset of the 1st car. For the $i$-th car, the parameters $L_{ti}$, $a_i$ and $b_i$ denote the car length, wheelsets' interval of each bogie, and bogies' interval, respectively. The distribution function $\phi(z)$ in Eq. (1) can be computed by summing up the distribution function $q_0(z)$ for each axle load of the train, computed as the deflection curve of an infinite beam of stiffness *EI* supported by springs of stiffness $s(\mathrm{N/m^2})$ under a unit axle load [37],