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A Review of Researches on Ground-Borne Vibrations with Emphasis on Those Induced by Trains

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ABSTRACT

In this paper, research works which have focused on the problem of ground-borne vibrations induced by traffic loads, especially those by the trains, are reviewed. Historically, many different approaches have been adopted to analyze traffic-induced vibrations, including analytical approaches, field measurements, empirical prediction formulas, and numerical simulations. The relevant literature is separated into these four major categories and reviewed accordingly. In particular, remarks are made regarding the development of techniques for wave isolation.

Key Words: infinite element, soil-structure interaction, railway trains, traffic-induced vibration, wave isolation

I. Introduction

Railway trains have been a major form of public transportation in the world for more than one and one-half centuries. There exist a wide variety of railway systems in the world, ranging from traditional weight freight and express passenger lines to modern metropolitan subways and high-speed railways. Different types of railway systems should meet different safety and environmental requirements. Even though advanced transportation systems, such as airlines, have made rapid progress in the last half century, the status of railways as a key transportation vehicle remains the same. As a matter of fact, in the last decade, many subways and high-speed railways, including those in Taiwan, have been completed or in the planning stages. Due to frequent construction of high speed railways and mass rapid transit systems worldwide, most highly developed cities or metropolitan areas have encountered the problem that transportation lines inevitably come cross or come close to vibration-sensitive residential or industrial areas. Although micro-vibrations induced by the transit of trains may not result in the collapse of buildings as earthquakes do, they have been known to cause delicate instruments located inside buildings to malfunction, while annoying the people living alongside the railways. Partly due to concerns expressed by the environmentalists, the problem of ground-borne vibrations induced by rail traffic has received increasing interest in recent years.

Vibrations can be amplified by the passage of trains due to the surface irregularities of wheels and rails, by the rise and fall of axles over sleepers and by the propagation of deformation patterns in the track and ground. Such vibrations are transmitted through the track structure, including the rails, sleepers, ballast and sub-layers, and propagate as waves through the soil medium, after which they can be sensed by the people living alongside the railway or over a tunnel through which a railway passes. In summary, the process of the transmission of vibrations from a train through the railway, ties and subsoils to the surrounding structures has four major phases: (1) generation, i.e., the excitation caused by the motion of trains over rails with irregular surfaces; (2) transmission, i.e., the propagation of waves through the surrounding soils; (3) reception, i.e., the vibrations received by nearby buildings; (4) interception, i.e., the reduction of vibrations using wave barriers, such as piles, trenches, isolation pads, etc. During each phase, there are various factors that can affect the final vibration levels to different degrees. The primary factors involved include the train type, train speed, embankment design, ground condition, building foundation, building type, and the distance between the railway and buildings. The lack of an in-depth understanding of these factors makes it difficult to analyze the problem. In certain circumstances, however, it is possible to estimate the levels of ground vibrations transmitted from roads or railways using a combination of empirical and theoretical results that have been made available.

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Previously, the problem of ground-borne vibrations has been dealt with mainly through four different approaches, i.e., the analytical approach, field measurement, empirical prediction models, and numerical simulation. In this paper, a general survey will be given for each of the four approaches, followed by a separate section on the isolation of traffic-induced vibrations using some control devices. The reason for reserving a separate section for this issue is that in the literature, the problem of wave isolation has been solved through different approaches. It is difficult to integrate the findings particularly related to this issue if they were split into different sections. All in all, we realize that the research on train-induced vibrations is voluminous and continues to grow rapidly. Some works have been published in languages other than English, especially those of Europe and Japan, where high-speed railways have been in operation for decades. It is almost impossible to give an exhaustive list of all the relevant papers. Only papers that were readily available to the authors and were written in English or Chinese will be cited in this paper.

II. Analytical Approaches

With an analytical approach, one uses theoretical models to describe each component of a source-path-receiver system. Because of the necessary simplifications and sub-divisions involved in modeling, exact analytical solutions for a practical problem are at present not available. The exact solutions obtained for some ideal cases, however, can give us insight into this problem and provide us with useful references for validating numerical simulation results and empirical prediction models.

1. Classical Theory of Elastic Wave Propagation

The pioneering work of Lamb (1904) contained most of the elements that are essential to analytical studies on the vibration sources and transmission paths in soils. In his work, Lamb investigated the disturbance generated in an elastic medium due to an impulsive force applied along a line or at a point on the semi-infinite surface or inside an unbounded full space. Such solutions can be easily extended to yield steady-state solutions for cases with loadings moving at constant speeds if a new coordinate system moving synchronously with the loadings is adopted. In reality, they have also been used by researchers as a basis for developing empirical prediction models. For these reasons, it is necessary to highlight the major features of the problem of an elastic half-space subjected to a point or line load, as was studied by Lamb (1904). Here, it should be realized that the same problems were analysed by a number of researchers at different times, including, in particular, Ewing *et al.* (1957), Fung (1965), Graff (1973), and Achenbach (1976), among others. In two somewhat tutorial papers presented by Gutowski and Dym (1976) and Dawn and Stanworth (1979), some major features of the elastic half-space problem were thoroughly discussed.

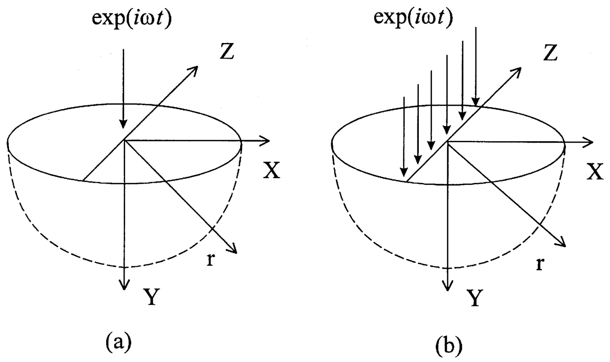

Fig. 1. Classical Lamb's problem with harmonic: (a) point load, (b) line load.

If an oscillating loading is applied to a homogeneous unbounded elastic space, two types of waves will emanate from the loading: compressional waves (P-waves) and shear waves (S-waves). In P-waves, a particle moves in the direction of propagation while in S-waves it moves in directions normal to that of propagation. For a homogeneous, elastic half-space, another type of waves, called Rayleigh waves (R-waves), occur on the free surface. An R-wave is a surface wave whose amplitude attenuates exponentially in the coordinate normal to the surface. Among the three type of waves, the speed of P-waves, c_P, is greater than that of S-waves, c_S, and the speed of R-waves, c_R, is the lowest. In honouring the contribution made by Lamb to the classical theory of wave propagation, the problems that were studied by him have been named after him and are together referred to as Lamb's problems. For the present purposes, two typical Lamb's problems are depicted in Fig. 1, in which (a) and (b) show a homogeneous elastic half-space subjected to an oscillating point load and a harmonic line load, respectively. In case (a), the R-waves attenuate along the surface inversely proportional to the square root of the distance from the point load; i.e., the decaying rate is proportional to $r^{-1/2}$, where r denotes the radial distance from the point load. The two body waves, i.e., the P-waves and S-waves, suffer substantial geometric attenuation, with their amplitudes decaying at a rate proportional to r^{-2} on the surface and to r^{-1} in the interior of the half-space. In the case of a harmonic line load applied to the half-space (Fig. 1(b)), the response is then typical of the spreading of cylindrical energy; the attenuation in the amplitude of the body waves is proportional to r^{-1} on the surface and to $r^{-1/2}$ in the interior. The R-waves in this instance do not suffer any geometric attenuation on the surface.

2. Elastic Medium Subjected to a Moving Load

With the continuous increase in the speed of trains worldwide, the effect of the speed of moving loads has drawn

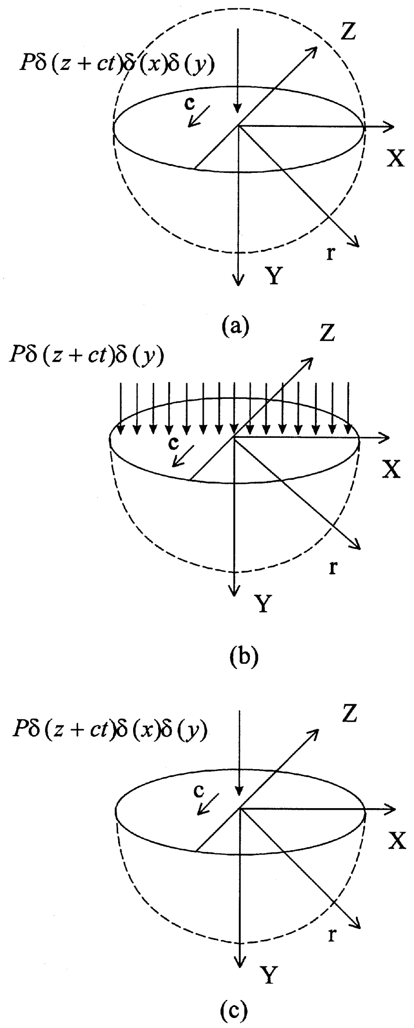

Fig. 2. Elastic body subjected to a load moving in negative z-direction: (a) unbounded elastic body with point load, (b) elastic half-space with line load, (c) elastic half-space with point load.

more attention than ever. One of the major concerns about train speed is the shock waves that may be produced as a train passes through some elastic barriers. It is well known that as an airplane passes through the sound barrier, a Mach radiation of shock waves can be observed. Likewise, when a moving object surpasses the characteristic speed of the waves in the surrounding medium, a significant radiation effect on the ground motion can be expected. Obviously, the classical theory of elastic wave propagation becomes insufficient in this case.

Once the classical problem of elastic wave propagation was understood to extent, many scientists in the field of soil dynamics began to extend the framework established by Lamb in order to analyze the problem of moving loads. Consider an elastic medium subjected to a load moving with speed c. This problem can be divided into three different cases: (1) the subsonic case ($c < c_S$): the loading is moving more slowly than the S-wave speed of the elastic medium; (2) transonic case ($c_S < c < c_P$): the load moves at a speed greater than the S-wave speed, but less than the P-wave speed; (3) the supersonic case ($c_P < c$): the load speed is greater than the P-wave speed. In this regard, three typical problems should be identified, as depicted in Fig. 2(a) – (c). Here, Fig. 2(a) shows an elastic unbounded space subjected to a moving point load. Figure 2(b) and (c) show an elastic half-space subjected to a moving line load and point load, respectively. Obviously, case (1) may find application in the computation of the response of soils around a tunnel through which a train passes. Case (3) represents the effect of an at-grade moving train. The major features and related literature for the three typical problems will be briefly discussed in the following.

A. Unbounded Elastic Body Subjected to Moving Point Load

Frỳba (1972) analyzed the responses of an unbounded elastic body subjected to a moving point load using the technique of triple Fourier integral transformation. From the close-formed solution he obtained, distinct differences can be observed between the responses in the subsonic, transonic, and supersonic cases. Based on the results obtained by Frỳba (1972) for a point load P moving with speed c in the negative z-direction, as shown in Fig. 2(a), the vertical displacements v in the elastic body at the instant $t = 0$ can be written as:

(1) subsonic:

$$v = \frac{P}{4\pi G M_2^2}\left(\frac{M_2^2}{R_2} + \frac{x^2}{r^4}(R_2 - R_1) - \frac{y^2 z^2}{r^4}\left(\frac{1}{R_2} - \frac{1}{R_1}\right)\right), \tag{1a}$$

(2) transonic:

$$v = \frac{P}{4\pi G M_2^2}\left\{\frac{M_2^2}{R_2}H(z - a_2 r) + \frac{x^2}{r^4}[R_2 H(z - a_2 r) - R_1] - \frac{y^2 z^2}{r^4}\left[\frac{1}{R_2}H(z - a_2 r) - \frac{1}{R_1} + \frac{a_2 r R_2}{z^2}\delta(z - a_2 r)\right]\right\}, \tag{1b}$$

(3) supersonic:

$$v = \frac{P}{4\pi G M_2^2}\left\{\frac{M_2^2}{R_2}H(z - a_2 r) + \frac{x^2}{r^4}[R_2 H(z - a_2 r) - R_1 H(z - a_1 R)] - \frac{y^2 z^2}{r^4}\left[\frac{1}{R_2}H(z - a_2 r) - \frac{1}{R_1}H(z - a_1 r) + \frac{r}{z^2}(a_2 R_2 \delta(z - a_2 r) - a_1 R_1 \delta(z - a_1 r))\right]\right\}, \tag{1c}$$

where

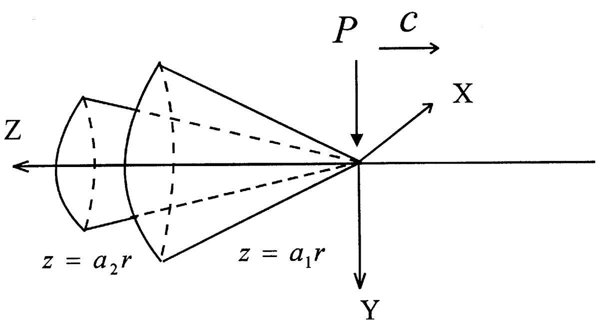

Fig. 3. Two Mach cones existing in an unbounded elastic body for a load moving at supersonic speeds.

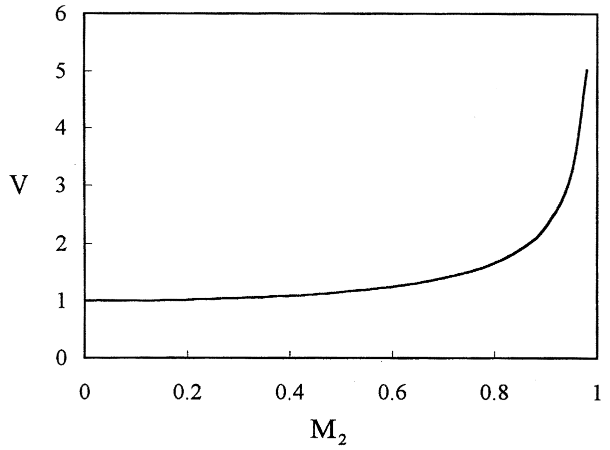

Fig. 4. Maximum vertical displacement vs. the S-wave Mach number (unbounded elastic body subjected to a moving point load).

$$a_i^2 = \left| 1 - M_i^2 \right|, \; r^2 = x^2 + y^2,$$

$$R_i^2 = z^2 + (1 - M_i^2) r^2, \; i = 1, 2. \tag{2}$$

Here, $M_1 = c/c_P$ and $M_2 = c/c_S$ denote the Mach numbers related to the P-waves and S-waves, respectively, G is the shear modulus of the elastic body, $H(x)$ the Heaviside function, and $\delta(x)$ the Dirac function. As can be seen from Eq. (1), the vertical displacement is symmetric to the x axis for the subsonic case. But when the load speed exceeds those of the P- and S-waves, the effects of the corresponding waves are confined to a region of the solid bounded by a trailing Mach cone with the apex at the loading point and moving with it. The P-wave Mach cone can be written as $z = a_1 r$ and the S-wave Mach cone as $z = a_2 r$ (Fig. 3). From Eq. (1c), one observes that no disturbances are induced ahead of the P-wave front. Based on Eq. (1a) for the subsonic case, the maximum vertical displacement v at the point ($x = 0$, $y = 1$ m, $z = 0$) can be plotted with respect to the S-wave Mach number M_2 as shown in Fig. 4, where the displacements are given in a normalized sense, i.e., $V = (4\pi G/P)v$. As can be seen, the displacement increases with the moving speed. The variation appears to be gradual in the range $M_1 < 0.6$, but for the range $M_1 > 0.6$, the displacement increases dramatically following the increase of M_2. Also, there exists a tendency for the displacement to become infinite, as the moving speed approaches the S-wave speed, i.e., as M_2 approaches unity.

B. Elastic Half-Space Subjected to a Moving Line Load

The two-dimensional problem of a line load moving with uniform subsonic speed over the surface of a uniform elastic half-space was first considered by Sneddon (1951), who gave a general integral solution for the subsonic case. Cole and Huth (1958), Fung (1965) and Frýba (1972) considered the same problem for a normal line load and obtained solutions for the subsonic, transonic and supersonic cases. The transient problem for a line load that suddenly appears on the surface of an elastic half-space and then moves with constant speed was considered by Payton (1967). From these works, it can be observed that if the load moves steadily at a speed equal to the R-wave speed, the response will become infinitely large. Furthermore, for the supersonic case, instead of the appearance of the two Mach cones shown in case (1), two Mach lines ($z = a_1 y$ and $z = a_2 y$) occur where the displacements have singularities.

C. Elastic Half-Space Subjected to a Moving Point Load

Eason (1965) studied the three-dimensional steady-state problem for a uniform half-space subjected to forces moving at uniform speeds. Besides the point forces, Eason also considered the case of moving forces distributed over a circular or rectangular area. The governing equations were solved by means of integral transform, with the resulting multiple integrals reduced to single finite integrals for the subsonic case. Gakenheimer and Miklowitz (1969) derived an expression for the transient displacements in the interior of an elastic half-space under a normal point load that is suddenly applied and then moves at a constant speed along the free surface. All the subsonic, transonic and supersonic cases were studied, with the inverse transform evaluated using the Carniard-de Hoop technique. The steady-state response for the same problem was also given by Frýba (1972) in integral form. Using a method similar to Eason's (Eason, 1965), Alabi (1992) studied the response due to an oblique moving point load applied on the free surface. By means of numerical integration, a parametric study was performed to investigate the effects of the load speed, distance and ground depth in the subsonic case. De Barros and Luco (1994) proposed a procedure for obtaining the steady-state displacements and stresses within a multi-layered viscoelastic half-space generated by a buried or surface point load moving along a horizontal straight line at subsonic, transonic or supersonic speeds. The effect of layering was considered by using an exact factorization for the displacement and stress fields in terms of the generalized transmission and reflection coefficients, following generally the procedure proposed by Luco and Apsel (1983). Using the Fourier transform and a special integration scheme, Yeh *et al.* (1997) obtained the response of an elastic half-space subjected to a moving point load for the subsonic case. Grundmann *et al.* (1999) studied the response of a layered half-space subjected to a single moving periodic load as well as a simplified train load. The inverse transformation was performed through a decomposition in wavelets (Lieb and Sudret, 1998), and the layered half-space was modeled using one-dimensional finite elements for the vertical direction in the transformed domain.

3. Summary of Solution Methods

In the early days, nearly all of the analytical studies on soil vibrations were carried out using the integral transformation techniques, which were considered to be efficient for studying moving load problems. The most frequently used technique was probably the one that utilizes the Fourier transformation for the length coordinates and the Laplace or Fourier transformation for the time coordinate. In the following, a summary will be given of the procedure for finding the solution along with some interesting results. As an illustration, consider a point load moving on the surface of an elastic half-space that covers the domain $y > 0$ (Fig. 2(c)). The equation of motion can be written as

$$G\nabla^2 u_i + (\lambda + G)u_{j,ji} + B_i = \rho \ddot{u}_i, \tag{3}$$

where the constants λ and G are the so-called Lamé's constants, u_i and B_i denote the displacement and body force components, respectively, and ρ the mass density. By applying the Fourier transformation three times each with respect to the two horizontal coordinates, x and z, and time t, Eq. (3) can be transformed from partial differential equations into ordinary differential equations with the vertical coordinate y serving as the only variable. After the boundary conditions on the free surface as well as the radiation and finiteness conditions at infinity are taken into account, one can solve the ordinary differential equations to obtain the response in the transformed domain. Theoretically, any type of external force applied on the surface can be solved in this manner. In practice, however, only in the cases of some particular forces, e.g., the point force to be considered below, can solutions be obtained analytically. For a load moving with a constant speed in the z direction, inversion of the Fourier transform with respect to z can be performed analytically, thereby enabling us to express the response in terms of a double integral with respect to the frequency ω and wave number k_x in the x direction as follows:

$$\begin{aligned}
U = \frac{2\pi G u}{P_y} &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \{\int_{-\infty}^{\infty} \frac{ik_x}{2Q}[(k^2 + k_x^2 - \frac{1}{2}k_S^2)e^{-m_1 y} \\
&\quad - m_1 m_2 e^{-m_2 y}]e^{-ik_x x}dk_x\}e^{-ikz}e^{i\omega t}d\omega, \\
V = \frac{2\pi G v}{P_y} &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \{\int_{-\infty}^{\infty} \frac{m_1}{2Q}[(k^2 + k_x^2 - \frac{1}{2}k_S^2)e^{-m_1 y} \\
&\quad - (k^2 + k_x^2)e^{-m_2 y}]e^{-ik_x x}dk_x\}e^{-ikz}e^{i\omega t}d\omega, \\
W = \frac{2\pi G w}{P_y} &= \frac{1}{2\pi}\int_{-\infty}^{\infty} \{\int_{-\infty}^{\infty} \frac{ik}{2Q}[(k^2 + k_x^2 - \frac{1}{2}k_S^2)e^{-m_1 y} \\
&\quad - m_1 m_2 e^{-m_2 y}]e^{-ik_x x}dk_x\}e^{-ikz}e^{i\omega t}d\omega,
\end{aligned} \tag{4}$$

where

$$\begin{aligned}
&k = \omega/c,\ k_P = \omega/c_P,\ k_S = \omega/c_S, \\
&Q = (k^2 + k_x^2 - \frac{1}{2}k_S^2)^2 - m_1 m_2 (k^2 + k_x^2), \\
&m_1 = (k^2 + k_x^2 - k_P^2)^{1/2}, \\
&m_2 = (k^2 + k_x^2 - k_S^2)^{1/2}.
\end{aligned} \tag{5}$$

Here, u, v, w denote the displacements in the x, y, z directions, respectively, and U, V, W are their normalized forms. Due to the existence of two radicals in the exponents of the inverse transform (as revealed by $m_1 = 0$ and $m_2 = 0$) and a singularity (occurring when $Q = 0$) in the integrands, evaluation of these integrals is itself a formidable task. As a matter of fact, most of the results obtained by early researchers were only presented in integral form. However, over the last decade, more and more researchers have tried to solve this integration problem using sophisticated numerical methods that can circumvent the singularities and yield the desired results. Based on an integral representation of the complete response in terms of the wave number, de Barros and Luco (1994) obtained results in the time domain using fast Fourier transformation of the frequency response, which in turn was obtained using an adaptive Filon quadrature algorithm over one horizontal wave number. Recently, Grundmann *et al.* (1999) applied the wavelet transformation to compute this inverse transform, by which means a substantial reduction in data can be obtained using an error-controlled procedure. The essential feature of the aforementioned two works is that they allow us to control and limit the computational errors by using an adaptive integration procedure.

In this study, the quadrature routines available in IMSL will be used to perform the inverse transform with respect to k_x and the fast Fourier transform with respect to ω in Eq. (4). For the cases of transonic speed and supersonic speed, the pole of the integrands can be shifted off the real k_x axis if material attenuation is considered. The material damping included herein is expressed in terms of the complex Lamé's constants, i.e., $G^* = G(1 + 2i\beta)$ and $\lambda^* = \lambda(1 + 2i\beta)$, where β denotes the hysteretic damping ratio.

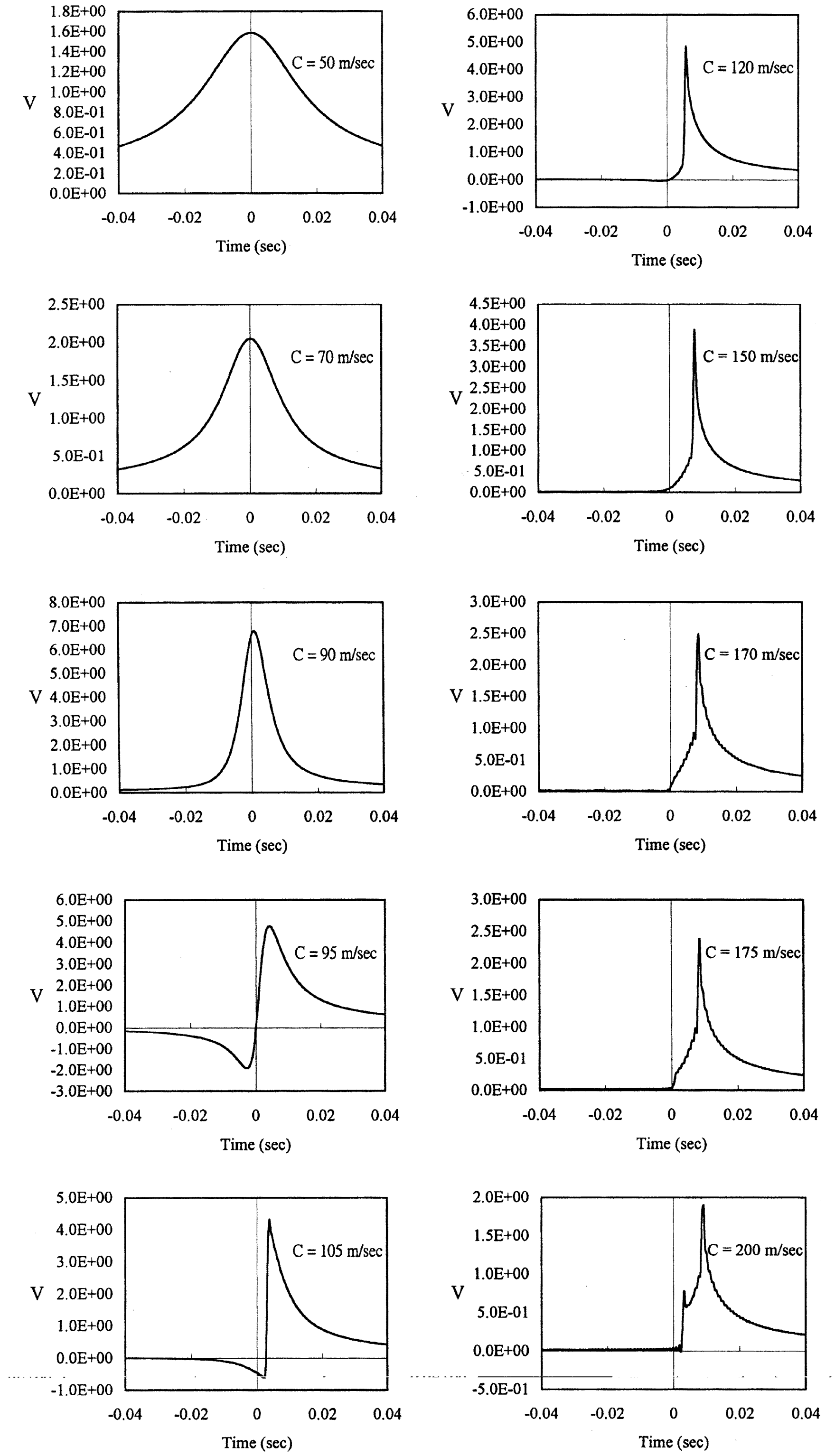

Fig. 5. Response of vertical displacement V at different load speeds for $(x, y, z) = (0, 1\text{ m}, 0)$.

With numerical integration, the normalized displacements $V = (2\pi G/P_y)v$ and $W = (2\pi G/P_y)w$ at the position y = 1 m beneath the moving point load under different speeds can be computed, and the results are plotted in Figs. 5 and 6, respectively. The numerical results were calculated for a uniform viscoelastic half-space characterized by c_S = 100

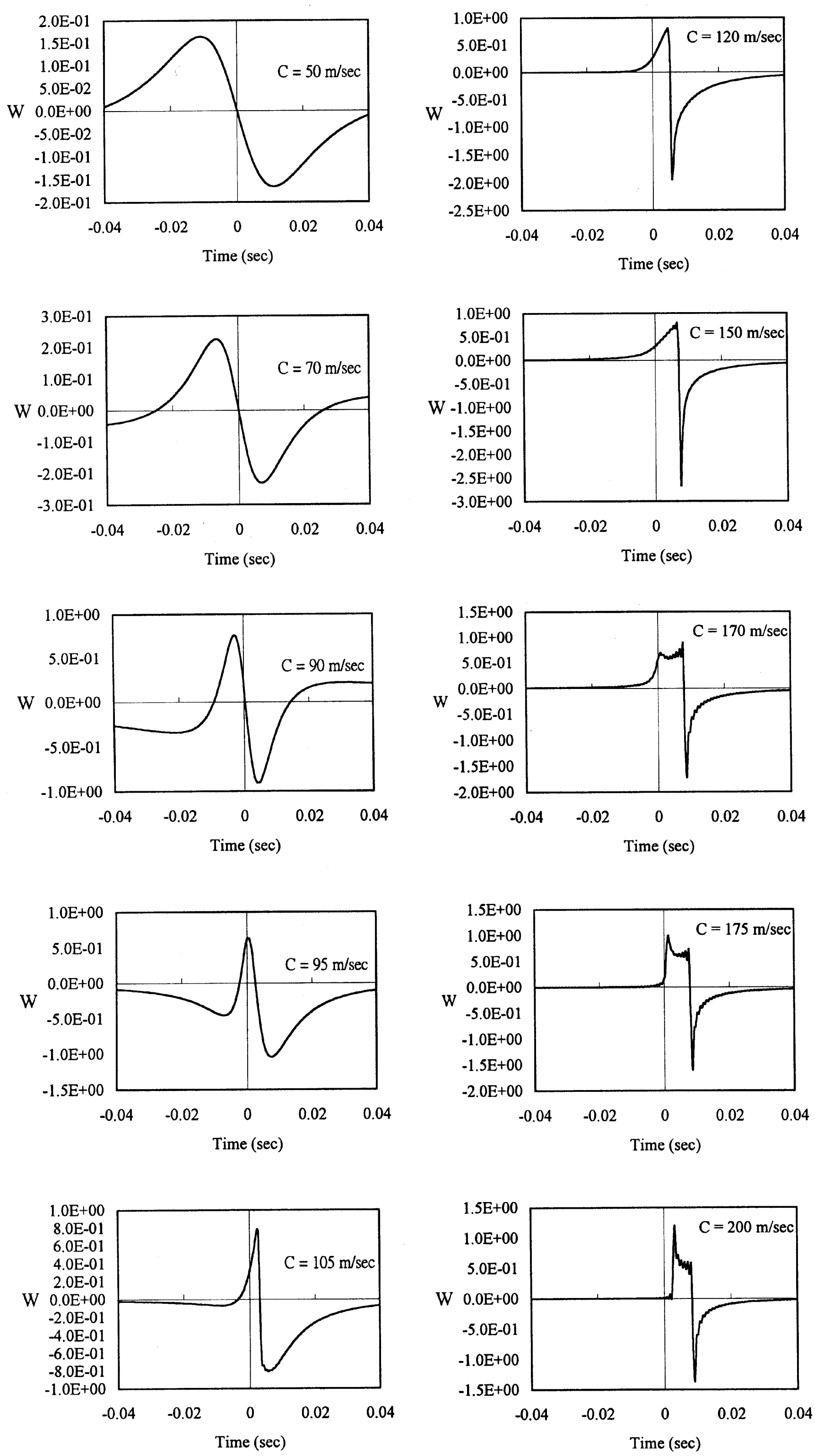

Fig. 6. Response of displacement W at different load speeds for $(x, y, z) = (0, 1\text{ m}, 0)$.

m/s, $c_P = 173.2$ m/s, $c_R = 92$ m/s and $\rho = 2000$ kg/m^3. The hysteretic damping ratio was taken as $\beta = 0.01$. In these figures, the instant $t = 0$ corresponds to the time at which the point load passes through the coordinate $z = 0$. As can been seen, the shape of the response for the load speed in the subsonic region ($c < 100$ m/s) varies drastically, depending on whether

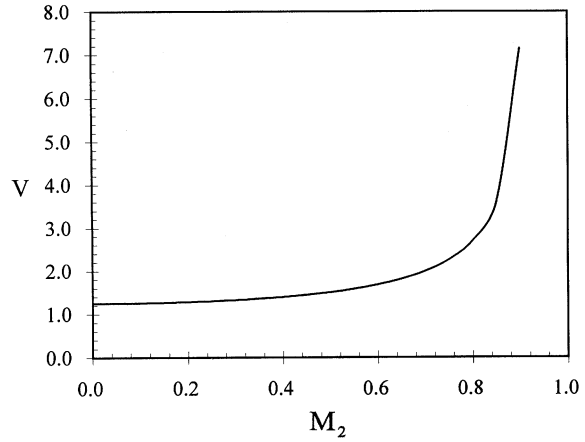

Fig. 7. Maximum vertical displacement vs. the S-wave Mach number. (elastic half-space subjected to a moving point load).

the load speed is lower or higher than the R-wave speed, c_R = 92 m/s. The vertical response is almost symmetric with respect to the axis perpendicular to the moving direction and pointing downward for load speeds lower than the R-wave speed. As the speed increases, the response begins to lose its symmetry due to the radiation effect of the Mach waves. Concerning the supersonic case (c = 200 m/s), the arrival of the P-wave front corresponds to the first peak in the response immediately after the instant t = 0, the S-wave front corresponds to the second peak, and the R-wave front comes immediately after the S-wave front.

For the subsonic case, the maximum vertical displacement V at the point y = 1 m beneath the point load vs. the S-wave Mach number M_2 is plotted in Fig. 7. Here, all the material properties are assumed to be identical to those used in the last case, except that $\beta = 0$ is used for hysteretic damping. Similar to the trend observed in Fig. 4, the vertical displacement increases with the load speed. However, for the present case, the displacement approaches infinity as the load speed gets closer to the R-wave speed, $M_2 = 0.92$. In order to investigate the effect of displacement attenuation with respect to the distance, the normalized vertical displacement V at y = 1 m beneath the point load is sketched for the range x = 0 ~ 20 m for different load speeds in Fig. 8. As can be seen, the displacement decreases dramatically with the distance in the region near the loading, but as the distance increases, the variation becomes quite small. This figure also indicates that for load speeds lower than 70 m/s, the influence of the load speed is not significant. For this case, the following are assumed for the uniform elastic half-space: c_S = 100 m/s, c_P = 173.2 m/s, and c_R = 92 m/s.

4. Beam on Elastic Half-Space Subjected to Moving Load

As mentioned above, when an object moves with a speed greater than the wave speed of the surrounding medium, a Mach cone is generated that moves with the object. For the case of a moving train, the moving load first acts on the rails and then is transmitted to the underlying half-space. Obviously, the characteristic wave speed of the rails and foundations should be considered as well. In the literature, a supporting railroad track has been modeled as a beam resting on a Winkler foundation by a number of researchers. For instance, Frỳba (1972) presented a detailed solution for the problem of a constant force moving along an infinite beam on an elastic foundation, considering all possible speeds and values of viscous damping. Based on the concept of equivalent stiffness for the supporting structure, a critical speed was identified for the moving load, at which the response of the beam becomes infinite. Such a speed corresponds exactly to the propagation speed of disturbances in the beam. For load speeds lower than the critical speed, the largest amplitude of waves occurs near the point of loading. On the other hand, for load speeds higher than the critical speed, the waves moving ahead of the load are smaller in wavelength and amplitude than those behind the load. The critical speed for an Euler-Bernoulli beam is the lowest bending wave speed, which can be given as

$$c_{cr} = \sqrt[4]{4kEI/m^2} \, , \tag{6}$$

in which m is the mass per unit length, EI the bending stiffness of the beam and k the coefficient of the Winkler foundation, which is usually assumed to be a constant. Duffy (1990) further examined the vibrations that arise when a moving, vibrating mass passes over an infinite railroad track lying on a Winkler foundation. Similar results were obtained.

After substituting the material properties for typical railroads into Eq. (6), many researchers, including Frỳba (1972) and Heckl *et al.* (1996), concluded that coincidence of the train speed with the critical speed is extremely unlikely. However, the accuracy of their results may have been affected

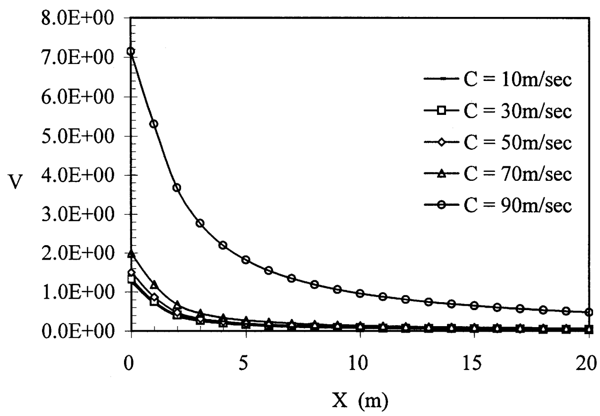

Fig. 8. Attenuation of vertical displacement V at different load speeds for $(y, z) = (1\ \text{m}, 0)$.

by the value used for the coefficient of elastic foundation k, which in practice is difficult to determine. Dieterman and Metrikine (1996, 1997) conducted a series of analyses to derive the equivalent stiffness of an elastic half-space interacting with a Euler-Bernoulli beam of finite width. They found that the equivalent stiffness depends mainly on the frequency and wave number of the beam. With this equivalent stiffness taken into account, the analysis indicated that there exist two critical speeds. One corresponds to the R-wave speed, and the other one is somewhat smaller than the R-wave speed. Both speeds can result in severe amplification of the beam displacement. Lieb and Sudret (1998) performed a similar analysis and found that severe displacements could be observed on the half-space underlying the rails at the critical speeds as well. Suiker *et al.* (1998) further studied the critical behaviour of a Timoshenko beam − half space system under a moving load. If highway traffic, instead of railroad traffic, is considered, a model with a plate on elastic foundations should be used. Kim and Roesset (1998) investigated the dynamic response of an infinite plate on an elastic foundation subjected to a moving load. The critical speed observed for such a case is

$$c_{cr} = \sqrt[4]{4kD/m^2}\ , \tag{7}$$

where D is the flexural rigidity of the plate, and m and k are the mass and stiffness of the foundation per unit area, respectively.

5. Sophisticated Loading Generation Mechanism

For continuously welded rails and perfect wheels, the most important mechanism of excitation of ground vibrations by moving trains is the quasi-static pressure exerted by the wheel axles onto the track. This pressure with certain patterns will move with the wheels. Krylov and Ferguson (1994) studied the ground vibration associated with railways using the Green function formalism, where the deflection curve of a beam lying on a Winkler foundation and subjected to a stationary point load was adopted as the shape of the pressure generated by each wheel on the rails. It is easy to see that the pressure is distributed and radiated to the ground by the sleepers. Through superposition of the elastic waves radiated by the sleepers caused by the passage of all the axles and by taking into account the time difference between the forces and their locations in space, a load generating mechanism that can capture the influence of the sleeper spacing, train length and train speed was constructed. As for the effect of subsoils, Krylov and Ferguson (1994) made use of the results obtained for the axisymmetric Lamb's problem for a half-space subjected to a vertical harmonic point load to determine the Green function but considered only the contribution of the R-waves. Krylov (1995) further extended this analysis to study the response caused by superfast trains, from which the Mach radiation on the soils can be observed as the train moves at a speed faster than the R-wave speed of the subsoil. In Takemiya's study (Takemiya, 1997), the same defection curve was adopted to account for the quasi-static pressure exerted by the wheel axles onto the ground. In this study, however, the sleeper spacing was not taken into account.

A random vibration method was used by Hunt (1991) to model road traffic-induced ground vibration. In his study, vehicles were modelled as two-axle systems, each with four degrees of freedom, and the ground as an elastic homogeneous half-space with viscous damping. Based on Lamb's solution (Lamb, 1904) for the half-space response generated by a harmonic load on the surface, he derived the elastic isotropic half-space frequency response function. Later, Hunt (1996) extended the analysis to compute the vibration transmitted by railways into buildings using the random process. More recently, Hao and Ang (1998) used a similar method to estimate the power spectral densities of traffic-induced ground vibrations. In order to circumvent the difficulties associated with numerical integration, they considered the contribution of the R-waves only and obtained an approximate closed-form solution.

III. Field Measurement

By means of field measurements, the response of existing installations can be obtained directly. When sufficient measurements are taken, a data base can be compiled, based on which the results can be analyzed statistically. These results serve as a basis for predicting vibration levels for similar installations. However, only after a statistically meaningful number of results have been made available for each case, can the effect of various parameter changes and corresponding vibration control measures be predicted (Melke and Kraemer, 1983). In addition, successful site measurements of structure and ground vibrations require sophisticated electronic equipment. It is desirable to employ high-sensitivity accelerometers, which can be placed at strategic points for simultaneous data collection. This requires a central data logger and calls for a number of long cables and remote amplifiers, which can transmit data over a long distance without picking up extraneous noises (Newland and Hunt, 1991). As a result, thorough empirical observation is the most time-consuming and expensive of the four approaches. Given below is a brief review of some of the experimental observations published in the literature.

Dawn and Stanworth (1979) presented a few of the experimental results that had been obtained in studies done on the British Railways. Melke and Kraemer (1983) proposed some schemes for analyzing field measurement data so that useful information could be extracted to establish a prediction model. From one-third octave band analysis to real experimental data, one crucial observation is that two peak levels occur in the frequency domain. One has a fixed value corresponding to the tunnel/soil natural frequency. And the other has a value that increases with the train speed corresponding to the sleeper passing frequency f_s, given as

$$f_s = c/l_s, \tag{8}$$

where c is the train speed and l_s the spacing between sleepers. Whenever the two peak frequencies coincide at a certain train speed, the vibration level will increase drastically due to the effect of resonance.

Based on the results of analysis of measurement data, Heckl *et al.* (1996) also made some remarks on the mechanisms that may be involved in vibration excitation caused by trains. He found that besides the sleeper passing frequency f_s, the wheel passing frequency f_a is also an important frequency of vibration induced by a moving train. Here, f_a can be given as

$$f_a = c/l_a, \tag{9}$$

in which l_a is the distance between two consecutive wheels. Since the distance between two consecutive wheels is not a constant for a real train, the wheel passing frequency is less apparent than the sleeper passing frequency. Other possible mechanisms involved in the excitation of ground vibrations by moving trains include the quasi-static pressure exerted by the wheel axles onto the track, the effects of joints in unwelded rails, unevenness of wheels or rails, and the effects of carriage- and wheel-axle bending vibrations which occur at their natural frequencies (Krylov and Ferguson, 1994).

Okumura and Kuno (1991) studied the effects of various factors on railway noise and vibration through a regression analysis of field data obtained at 79 sites along 8 traditional railway lines in an urban area in Japan. Among the six factors they used to explain the vibration peak levels, i.e., the distance, railway structure, train type, train speed, train length and background vibration, they found that the influence of distance was the greatest. The second prominent factor was background vibration, which was considered to be characteristic of the soil properties at each site. They also reported that the influence of train speed was not so obvious. This observation can be attributed to the fact that the field data were collected from traditional railways, whose running speeds were generally under 100 km/h (27.77 m/s), far lower than the R-wave speed for typical soils. Regarding the influence of railway structures, the vibration levels for the concrete bridges and retaining walls are lower than those for at-grade structures.

Takemiya (1998a, 1998b) analyzed field data collected alongside one of the Shinkansen railways, which has an average speed of around 240 km/hr, during the train passage. He concluded that the high-speed train generated rather impulsive ground motions of short duration which corresponded well with the wheel distance. Consequently, the vibration property could be modeled quite well, given the information of the wheel distance and the number of cars connected. Based on his observation, it can be concluded that the response features are significantly different for different types of supporting structure systems. For instance, the at-grade track reflects much more waves through the soil layers in the ground while the viaduct type involves structure-borne vibration, in which the frequency contents are closely related to the soil-structure interaction.

Lang (1988) performed some experiments to test the effectiveness of floating concrete slabs and trenches in isolating the vibrations of buildings located near a track. The results indicated that both methods were effective in reducing vibrations, but that the barriers appeared to be more effective in reducing vibrations near the track than those farther away.

IV. Empirical Prediction Models

Due to the lack of a comprehensive understanding of excitation generation mechanisms related to railway trains and the difficulty of determining accurate values for soil properties, modeling an entire system precisely is not an easy task. One way is to construct a simplified but reasonable model for predicting the responses based on some empirical and theoretical results. Most of the prediction models are composed of several separable independent formulas, each of which serves as a control parameter and can affect, to a certain extent, the final response. A simple prediction model such as this can be used to provide tentative estimations when one cannot afford to conduct extensive individual measurements immediately.

Gutowski and Dym (1976) and Verhas (1979) combined the measurement and theory into a predictive model, which was given in a simplified form of an attenuation function by taking into account the effects of material attenuation and geometrical attenuation. Kurzweil (1979) presented a model for predicting the vibration in buildings due to a train passing by, in which the vibration attenuation due to propagation through the ground, the ground-building interaction and the propagation in the building were considered. Melke (1988) proposed a procedure for predicting the structure-borne noise and vibration caused by underground railway lines. Based on analytical techniques and laboratory measurements, he used a chain of transmission losses, including track transmission loss, tunnel transmission loss, ground transmission loss, and building transmission loss, to predict the final velocity level in the building. Trochides (1991) presented a simple method for predicting excitation levels due to ground-borne vibrations in buildings located near subways. This model is based on approximate impedance formulas for the tunnel and the structure, and on simple energy considerations. Comparisons between calculations and measurements of scaled models showed that the predictions were generally acceptable for design purposes. Using a statistical formulation, Madshus *et al.* (1996) proposed a semi-empirical model for predicting low frequency vibration, based on a large number of vibration measurements obtained in Norway and Sweden. To make possible unified and systematic handling of the empirical data, a database was established, too. This model includes five separable statistically independent factors, i.e., the train type specific vibration level, speed factor, distance factor, track quality factor, and building amplification factor.

V. Numerical Simulation

Concerning the literature on ground-borne vibrations, most of the early researches were conducted using analytical or experimental approaches. When an analytical approach was adopted, however, restrictions were often imposed on the geometry and material properties of the problem considered, as closed-form solutions cannot be easily obtained for other complex conditions. On the other hand, although the results obtained using the experimental approaches appear to be most reliable and to be close to those for real situations, an exhaustive field testing was very expensive. Starting in the mid 1970s, with the advent of high-performance computers, various numerical methods began to emerge as effective tools for solving wave propagation problems, including the finite element method, boundary element method, and their variants.

In the last decade, a great portion of the studies on wave propagation problems focused on use of the boundary element method. The relevant works can be found in the review papers by Beskos (1987, 1997). One advantage of the boundary element method is that radiation damping can be accurately taken into account using suitable fundamental solutions. However, this method is not suitable for simulating the irregularities in the geometry and materials of the structure and underlying soils, which may be encountered in practical situations. Although, nowadays, the boundary element method has the ability to deal with inhomogeneity in geometry as well, this approach incurs much more complicated Green's function or interior subdivision of the domain considered.

On the other hand, the finite element method has the advantage of being applicable to almost arbitrary geometric conditions, thus allowing us to include the embedded structures and multi-layering of the soil deposits. Therefore, as far as the vibration of structures and surrounding soils is concerned, a finite element representation remains the most convenient one. A major disadvantage of the finite element method is that the soil, which is semi-infinite by nature, can only be modeled using elements of finite size. Consequently, the radiation damping that accounts for the loss of energy due to outward traveling waves cannot be modeled adequately. To overcome this disadvantage, another method is needed to model the infinite region, which leads us to the so-called hybrid method. By means of the hybrid method, a soil-structure system is divided into two subsystems, i.e., the near field and the far field (Fig. 9). The near field can be modeled by using

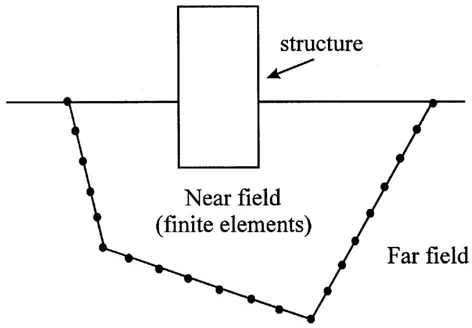

Fig. 9. Schematic of the hybrid method.

finite elements as usual. However, an accurate representation of the far field requires the establishment of an impedance matrix that can relate the nodal forces to the nodal displacements for the far field through the interface shown as solid dots in Fig. 9. In the literature, there exist a number of methods for modeling the far field domain, including the traditional boundary element method, consistent boundary, transmitting boundary, viscous boundary, superposition boundary, paraxial boundary, double-asymptotic boundary, extrapolation boundary, multi-direction boundary, infinite elements, and the so-called consistent infinitesimal finite-element cell method. A discussion of the advantages and disadvantages of each of these methods can be found in Wolf and Song (1996) and will not be recapitulated here.

Owing to its flexibility, the hybrid method has often been used to deal with problems involving wave barriers, buildings, embankments, layered soils, rails and tracks. According to Gutowski and Dym (1976), it is reasonable to simulate the passage of train loads by using a moving line load, provided that the distance of the receiver, i.e., the point of observation, from the track is less than $1/\pi$ times the length of the train. As can be seen in the literature, most researches on ground-borne vibrations have been based on two-dimensional modeling which assumes that the plain strain condition is valid. It is only for some very special cases that three-dimensional modeling has been adopted. In the following, a brief review will be given of the two types of modeling.

1. Two-Dimensional Modeling

Under the conditions that the external loading can be assumed to be an infinite line load, and that the material and geometric properties of the system in the direction along the line load are identical, the plane strain condition applies, and two-dimensional modeling can be adopted. Balendra *et al.* (1989) used the finite elements along with the viscous boundary to investigate the vibration of a subway-soil-building system in Singapore. Thiede and Natke (1991) adopted a similar method to study the influence of the variation in thickness of subway walls. Laghrouche and Le Houedec (1994) used the finite element method incorporated with a consistent boundary to study the effectiveness of an elastic mattress placed under a railway to reduce traffic-induced ground vibration. Hung (1995) and Yang and Hung (1997) combined the finite and infinite elements to investigate the effect of trenches and elastic foundations in reducing train-induced vibration. Kuo (1996) used the same procedure to study the vibration in buildings induced by machines or passing vehicles.

2. Three-Dimensional Modeling

Consider a system consisting of a railway, an underground tunnel and soils. It is reasonable to assume that the material and geometric properties are identical along the direction of the railway. Naturally, before the external loading effect is taken into account, the two-dimensional assumption remains valid. However, as the train speed increases and approaches the critical load, the two-dimensional model becomes inadequate for simulating the effect of Mach radiation. In reality, this problem is two-dimensional in geometry but three-dimensional in physics. Strictly speaking, a problem such as this should be analyzed using the three-dimensional model. However, for a geometrically two-dimensional problem, although simulation of a solid using the three-dimensional finite elements is straightforward in theory, it is not economical from the point of view of computation.

Let us examine Eq. (4), which shows the response for the case of a moving point load traveling in the z direction. If we extract the term $\exp(-ikz)\exp(i\omega t)$ from this equation, only variables x and y will be left. Thus, it is possible to discretize the system on the X-Y plane only if the following displacement field is adopted:

$$u = e^{-ikz}\sum N_i u_i \quad v = e^{-ikz}\sum N_i v_i \quad w = e^{-ikz}\sum N_i w_i, \qquad \textbf{(10)}$$

in which N_i denotes the shape function for the finite element. In this way, a three-dimensional system can be reduced to an assembly of two-dimensional elements with the traveling effect of the waves faithfully retained. Notice that because the elements used are plane elements, such a model cannot be regarded as a truly three-dimensional one. This has been referred to as a 2.5-dimensional model, as proposed by Hwang and Lysmer (1981), who studied the response of underground structures under traveling seismic waves. To the knowledge of the authors, Hanazato *et al.* (1991) were the first to apply this method to the analysis of traffic-induced vibrations. Using this method, the weights, speed, intervals, and vibrating conditions of vehicles can all be taken into account. In the study by Hanazato *et al.* (1991), the near field was modeled by the finite elements and the far field by thin-layered elements. Recently, Takemiya (1997) also used similar finite elements to model an embankment and used the boundary element procedure to simulate the underlying layered soils with discretization along the depth for the Green function involved. For the purpose of illustration, we shall evaluate here the response of an elastic half-space subjected to a point load moving at a speed of 70 m/s by means of 2.5-dimensional finite elements along with 2.5-dimensional infinite elements. The infinite element used is a revised version of a two-dimensional infinite element derived by the authors (Yang *et al.*, 1996). The elastic half-space is characterized by $c_S = 100$ m/s, $c_P = 173.2$ m/s, and $c_R = 92$ m/s. The time history of the normalized displacements, W and V, at the position $(x, y, z) = (0, 1\text{ m}, 0)$ is depicted in Fig. 10, in which the calculated results obtained using the finite/infinite elements are compared with the analytical results obtained by Eason (1965). As can be seen, this proposed method can simulate the effect of a moving load very well even though only the plane elements have been used.

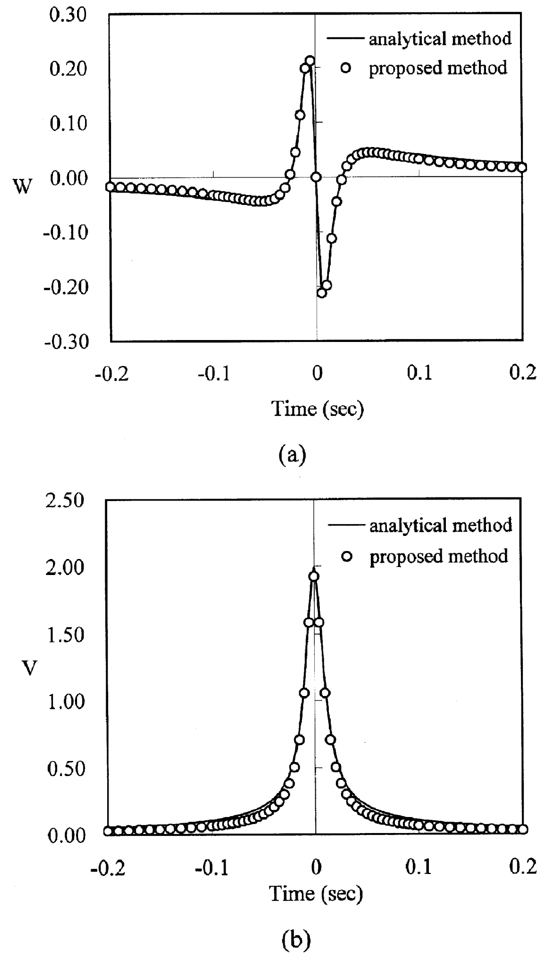

Fig. 10. Response of normalized displacements at c = 70 m/sec for $(x, y, z) = (0, 1\text{ m}, 0)$: (a) Displacement W, (b) Displacement V.

VI. Isolation of Vibration

A number of methods have been developed to control ground-borne vibrations. The common countermeasures include the installation of trenches, wave impeding barriers and floating slab tracks. In what follows, the major features and literature associated with each type of wave barrier will be discussed. Other possible methods of railway vibration reduction include the installation of very thick tunnel walls, resilient foundation under buildings (Newland and Hunt, 1991), increasing the tunnel depth, rail grinding and wheel truing, and insertion of rail pads, under-sleeper pads, ballast mats, etc. (Wilson *et al*., 1983).

1. Wave Isolation by Trenches

Trenches, including open and in-filled ones, have been used for years as wave barriers to isolate vibrations in machine foundations. The relevant literature on this subject is abundant. Investigation based on an experimental approach to studying the screening effect of open trenches was first performed by Woods (1968). Using the lumped mass method, Lysmer and Waas (1972) studied the effectiveness of a trench in reducing the horizontal shear wave motion induced by a harmonic load acting on a rigid footing lying on the horizontal layer. Segol *et al*. (1978) used the finite elements, along a special non-reflecting boundary, to investigate the isolation efficiency of open and bentonite-slurry-filled trenches in layered soils. Yang and Hung (1997) used the finite/infinite elements to analyze parametrically the isolation effect of open trenches, in-filled trenches and elastic foundations. Other related works that should be mentioned here include those of Aboudi (1973), Emad and Manolis (1985), Beskos *et al*. (1986, 1990), Ahmad and Al-Hussaini (1991), Ni *et al*. (1994), Al-Hussaini and Ahmad (1996), Ahmad *et al*. (1996) and Yeh *et al*. (1997). Summing up the results obtained in the works cited above, the most important requirement for a trench to achieve good isolation is that the trench should have a depth on the order of the surface wave length. Therefore, the isolation of ground-borne vibrations by trenches is effective only for moderate to high frequency vibrations.

2. Wave Isolation Using a Wave Impeding Block

Because of the presence of a rigid base, a soil stratum has some intrinsic eigenmodes by which the waves transverse, according to Wolf (1985). No vibration eigenmodes can be induced below the cut-off frequency of the soil stratum, which equals $C_p/(4h)$ for the vertical injected compressional waves, and equals $C_s/(4h)$ for the shear waves, with h denoting the depth of the soil stratum. It is, therefore, possible to take advantage of this vibration transmitting behaviour of the soil layer over a bedrock to impede the spreading of vibrations by installing an artificial stiff plate at a certain depth below the source. This idea leads to that of installing a so-called wave impedance barrier (WIB).

Among the researchers who have works conducted on the subject, the following should be mentioned: Schmid *et al*. (1991), Antes and von Estorff (1994) and Takemiya and Fujiwara (1994). All of these studies showed that the WIB can effectively reduce ground-borne vibrations. If artificial bedrock is used, the foundation and soil vibrations can be significantly reduced, but wave propagation into the surrounding area cannot be totally impeded because the artificial bedrock also vibrates. The effectiveness of the artificial bedrock can be improved by increasing its stiffness. Shielding of the building from soil vibrations can also be achieved by installing artificial bedrock directly beneath the building. From the construction point of view, a WIB with a rectangular shape requires a substantial amount of excavation of the soils before the concrete block is installed inside the soil. To overcome this drawback, the rectangular WIB was recently modified by Takemiya (1998a, 1998b) to obtain an X shape, and this is referred to as the X-WIB. Such a device can be constructed using the soil improvement procedure at sites by mixing and injecting the cement paste directly into the soils.

3. Floating Slab Track

Floating slab tracks, which basically consist of concrete slab tracks supported by resilient elements, have been widely used in modern rail transit systems (Wilson *et al*., 1983). It is well known that greater effectiveness can be achieved in reducing ground-borne vibration and noise at frequencies above $\sqrt{2}$ times the vertical resonance frequency of the floating slab system. However, when the frequency is equal or close to the resonant frequency, vibrations will be greatly amplified. The design which employs floating slab tracks assumes the existence of a single-degree-of-freedom system, in which the lumped mass includes that of the floating slab and the unsprung mass of the train, and in which the spring stiffness is determined by the supporting resilient pads. In order to increase the effectiveness of the floating slab track, that is, to lower the resonant frequency, the mass of the floating slab should be made as large as possible, as the resilient pads have to maintain a minimum level of rigidity to ensure rail stability under full axle loads. Such highly resilient elements can be incorporated at many locations in the transmission path to reduce vibration. Many different devices can be used as resilient elements, e.g., rubber spring under the rails, the Cologne egg (Esveld, 1989), ballast, resilient devices under the sleepers or the plates that support the rails, or a foam rubber mat under the ballast (Heckl *et al*., 1996).

Balendra *et al*. (1989) used a two-dimensional finite element model to compare the effects of two different supporting systems, a direct fixation system and a system with a floating slab. It is found that the vibration levels in a floating slab track system exceed those in a direct fixation track system in the low frequency range. However, in the high frequency range, a floating slab track system behaves as an effective vibration isolator. Grootenhuis (1977) introduced several types of floating track slabs that have been used and proposed a new design that can be built inside a bored tunnel without increasing the tunnel diameter. Wilson *et al*. (1983) also studied the effectiveness of a floating slab trackbed for a rapid transit system in Washington, D.C., U.S.A.

VI. Concluding Remarks

An overall review arranged in an approach-oriented manner on the vibration issues associated with railways has been presented. Also reviewed have been countermeasures used to achieve vibration mitigation. Regardless of which approach was used, each paper cited played a role in advancing research on this subject. The theoretical results serve as useful references for developing other methods. They can help us understand the major factors affecting each problem, such as the train speed, distance and soil condition, and evaluate the relative influence of each of them. Performing complete measurement of train-induced vibration in the field is a formidable task, not only because the appropriate equipment is not always available, but also because a site with real tracks and trains that is suitable for testing may be difficult to find. For these reasons, a database compiled from the data of field measurements would be highly valuable. It could help us identify the key factors that contribute most to the overall dynamic response, such as the spacing of sleepers, the spacing of wheels, unsprung masses and the type of track supporting the structure. The empirical prediction model seems to be the roughest among the four approaches considered. It enables engineers to draw immediate conclusions when time for tedious finite element analysis and extensive experiment is lacking. With the rapid development of high-performance computers, numerical simulation has emerged as a very effective tool for modeling wave propagation problems. In fact, for many practical engineering problems, the numerical approach remains the only one that can be employed. Nevertheless, the reliability of numerical simulation for predicting vibration levels depends largely on the accuracy of the input data and the choice of an appropriate underlying theory, which can be evaluated through comparison with results from experiments and theoretical analysis.

The most complex process among the four processes mentioned in the introduction section for vibration transmission is the source generation mechanism. In the literature, most reports have considered only the effect of quasi-static pressure acted upon by axle loads. In reality, however, there may exist dynamic terms generated by the unevenness of the wheels and rails, or associated with the sleeper passing frequency, rail passing frequency or resonance in the wagon or coach suspension. All these factors should be taken into account in future studies.

From the results obtained by means of analytical methods, we know that if a train travels faster than the propagation speed of the ground vibration, a shock wave will be generated in the ground. This phenomenon should not be regarded merely as a mathematical result, but one which may actually arise due to the continuous increase of train speeds. For example, speeds over 500 km/hr have been achieved on an experimental track in France (Krylov, 1995). In May 1990, nine runs of TGV trains moving at over 500 km/hr or 138.8 m/s were conducted by the French Railway Company (SNCF) on a section of track between Courtalain and Tours. These speeds surpassed the speed of the Rayleigh waves in the soils. As a result, a significant radiation effect on the ground vibrations was visible in these areas, which led to restrictions on the speed for the TGV trains on that section of track (Dieterman and Metrikine, 1996). Measurements made by the railway companies in Switzerland (SBB), France (SNCF), Germany (DB), Netherlands (NS) and Great Britain (BR) have also confirmed that the vertical movement of a track is amplified when a train moves at a speed on the order as the Rayleigh wave speed of the subsoil (Dieterman and Metrikine, 1997). Most of the previous works on train-Rayleigh wave behavior employed theoretical approaches. However, as this phenomenon is becoming not merely a theoretical issue, but also a real one, much more realistic models should be adopted to study its effect. This can be done primarily by means of numerical simulation. On the other hand, apart from passively setting a speed limit and/or improving the supporting subsoil, few active countermeasures for reducing vibration at critical speeds have been proposed. As far as the critical speed is concerned, further research should be conducted to search for alternative ways to reduce vibration, and the effectiveness of traditional wave barriers, including those mentioned in the preceding section, should be re-examined.

This review is offered with the hope that it may provide some information useful for evaluating the environmental effects of the high-speed railway that will be constructed in Taiwan and elsewhere. In addition, the results from the literature cited herein may serve as good references for further investigations.

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References

Aboudi, J. (1973) Elastic waves in half-space with thin barrier. *J. Eng. Mech. Div*., ASCE, **99**(EM1), 69-83.

Achenbach, J. D. (1976) *Wave Propagation in Elastic Solids*. North-Holland Publishing Company, New York, NY, U.S.A.

Ahmad, S. and T. M. Al-Hussaini (1991) Simplified design for vibration screening by open and in-filled trenches. *J. Geot. Eng*., ASCE, **117**(1), 67-88.

Ahmad, S., T. M. Al-Hussaini, and K. L. Fishman (1996) Investigation on active isolation of machine foundations by open trenches. *J. Geot. Eng*., ASCE, **122**(6), 454-461.

Alabi, B. (1992) A parametric study on some aspects of ground-borne vibrations due to rail traffic. *J. Sound Vibr*., **153**(1), 77-87.

Al-Hussaini, T. M. and S. Ahmad (1996) Active isolation of machine foundations by in-filled trench barriers. *J. Geot. Eng*., ASCE, **122**(4), 288-294.

Antes, H. and O. von Estorff (1994) Dynamic response of 2D and 3D block foundations on a halfspace with inclusions. *Soil Dyn. Earthquake Eng*., **13**, 305-311.

Balendra, T., K. H. Chua, K. W. Lo, and S. L. Lee (1989) Steady-state vibration of subway-soil-building system. *J. Eng. Mech*., ASCE, **115** (1), 145-162.

Beskos, D. E. (1987) Boundary element methods in dynamic analysis. *Appl. Mech. Rev*., **40**, 1-23.

Beskos, D. E. (1997) Boundary element methods in dynamic analysis: Part II: 1986-1996. *Appl. Mech. Rev.*, **50**(3), 149-197.

Beskos, D. E., B. Dasgupta, and I. G. Vardoulakis (1986) Vibration isolation using open or filled trenches, Part 1: 2-D homogeneous soil. *Comp. Mech*., **1**(1), 43-63.

Beskos, D. E., K. L. Leung, and I. G. Vardoulakis (1990) Vibration isolation studies in non-homogeneous soils. In: *Boundary Elements in Mech. & Electrical Eng*., pp. 205-271. C.A. Brebbia and A. Chaouet-Miranda Eds., Springer-Verlag, Berlin, Germany.

Cole, J. and J. Huth (1958) Stresses produced in a half plane by moving loads. *J. Appl. Mech*., ASME, **25**, 433-436.

Dawn, T. M. and C. G. Stanworth (1979) Ground vibrations from passing trains. *J. Sound Vibr*., **66**(3), 355-362.

de Barros, F. C. P. and J. E. Luco (1994) Response of a layered viscoelastic half-space to a moving point load. *Wave Motion*, **19**, 189-210.

Dieterman, H. A. and A. V. Metrikine (1996) The equivalent stiffness of a half-space interacting with a beam. Critical velocities of a moving load along the beam. *European J. Mech. A/Solids*, **15**(1), 67-90.

Dieterman, H. A. and A. V. Metrikine (1997) Steady-state displacements of a beam on an elastic half-space due to a uniformly moving constant load. *European J. Mech. A/Solids*, **16**(2), 295-306.

Duffy, D. G. (1990) The response of an infinite railroad track to a moving, vibration mass. *J. Appl. Mech*., ASME, **57**, 66-73.

Eason, G. (1965) The stresses produced in a semi-infinite solid by a moving surface force. *Int. J. Eng. Sci*., **2**, 581-609.

Emad, K. and G. D. Manolis (1985) Shallow trenches and propagation of surface waves. *J. Eng. Mech*., ASCE, **111**(2), 279-282.

Esveld, C. (1989) *Modern Railway Track*. MRT-Productions, Duisburg, Germany.

Ewing, W. M., W. S. Jardetzky, and F. Press (1957) *Elastic Waves in Layered Media*. McGraw-Hill, New York, NY, U.S.A.

Fryba, L. (1972) *Vibration of Solids and Structures under Moving Loads*. Noordhoff International Publishing, Groningen, The Netherlands.

Fung, Y. C. (1965) *Foundations of Solid Mechanics*. Prentice-Hall, Englewood ` Cliffs, NJ, U.S.A.

Gakenheimer, D. C. and J. Miklowitz (1969) Transient excitation of an elastic half space by a point load traveling on the surface. *J. Appl. Mech.*, ASME, **36**, 505-515.

Graff, K. F. (1973) *Wave Motion in Elastic Solids*. Dover Publications, New York, NY, U.S.A.

Grootenhuis, P. (1977) Floating track slab isolation for railways. *J. Sound Vibr*., **51**(3), 443-448.

Grundmann, H., M. Lieb, and E. Trommer (1999) The response of a layered half-space to traffic loads moving along its surface. *Archive Appl. Mech*., **69**, 55-67.

Gutowski, T. G. and C. L. Dym (1976) Propagation of ground vibration: a review. *J. Sound Vibr*., **49**(2), 179-193.

Hanazato, T., K. Ugai, M. Mori, and R. Sakaguchi (1991) Three-dimensional analysis of traffic-induced ground vibrations. *J. Geot. Eng*., ASCE, **117** (8), 1133-1151.

Hao, H. and T. C. Ang (1998) Analytical modeling of traffic-induced ground vibrations. *J. Eng. Mech*., ASCE, **124**(8), 921-928.

Heckl, M., G. Hauck, and R. Wettschureck (1996) Structure-borne sound and vibration from rail traffic. *J. Sound Vibr*., **193**(1), 175-184.

Hung, H. H. (1995) *Vibration of Foundations and Soils Generated by High-Speed Trains* (in Chinese). M.S. Thesis. Dept. Civil Eng., Nat. Taiwan Univ., Taipei, Taiwan, R.O.C.

Hunt, H. E. M. (1991) Stochastic modelling of traffic-induced ground vibration. *J. Sound Vibr*., **144**(1), 53-70.

Hunt, H. E. M. (1996) Modelling of rail vehicles and track for calculation of ground-vibration transmission into buildings. *J. Sound Vibr*., **193** (1), 185-194.

Hwang, R. N. and J. Lysmer (1981) Response of buried structures to traveling waves. *J. Geot. Eng. Div*., ASCE, **107**(GT2), 183-200.

Kim, S. M. and J. M. Roesset (1998) Moving loads on a plate in elastic foundation. *J. Eng. Mech*., ASCE, **124**(9), 1010-1017.

Krylov, V. V. (1995) Generation of ground vibration by superfast trains. *Appl. Acoustics*, **44**, 149-164.

Krylov, V. and C. Ferguson (1994) Generation of low frequency ground vibrations from railway trains. *Appl. Acoustics*, **42**, 199-213.

Kuo, J. (1996) *Structure and Soil Vibrations Induced by Machines or Passing Vehicles*. M.S. Thesis. Dept. Civil Eng., Nat. Taiwan Univ., Taipei, R.O.C.

Kurzweil, L. G. (1979) Ground-borne noise and vibration from underground rail system. *J. Sound Vibr*., **66**(3), 363-370.

Laghrouche, O. and D. Le Houedec (1994) Soil-railway interaction for active isolation of traffic vibration. In: *Adv. in Simulation & Interaction Techniques*, pp. 31-36. M. Papadrakakis and B.H.V. Topping Eds., Civil-Comp Press, Edinburgh, Scotland, U.K.

Lamb, H. (1904) On the propagation of tremors over the surface of an elastic solid. *Phil. Trans. Roy. Soc. London, Ser. A*, CCIII **1**, 1-42.

Lang, J. (1988) Ground-borne vibrations caused by trams, and control measures. *J. Sound Vibr*., **120**(2), 407-412.

Lieb, M. and B. Sudret (1998) A fast algorithm for soil dynamics calculations by wavelet decomposition. *Archive Appl. Mech*., **68**, 147-157.

Luco, J. E. and R. J. Apsel (1983) On the Green's functions for a layered half-space. Part I. *Bull. Seismological of America*, **73**(4), 909-929.

Lysmer, J. and G. Waas (1972) Shear waves in plane infinite structures. *J. Eng. Mech. Div*., ASCE, **98**(EM1), 85-105.

Madshus, C., B. Bessason, and L. Hårvik (1996) Prediction model for low frequency vibration from high speed railways on soft ground. *J. Sound Vibr*., **193**(1), 195-203.

Melke, J. (1988) Noise and vibration from underground railway lines: proposals for a prediction procedure. *J. Sound Vibr*., **120**(2), 391-406.

Melke, J. and S. Kraemer (1983) Diagnostic methods in the control of railway noise and vibration. *J. Sound Vibr*., **87**(2), 377-386.

Metrikine, A. V. and H. A. Dieterman (1997) The equivalent vertical stiffness of an elastic half-space interacting with a beam, including the shear stresses at the beam-half-space interface. *European J. Mech. A/Solids*, **16**(2), 515-527.

Newland, D. E. and H. E. M. Hunt (1991) Isolation of buildings from ground vibration: a review of recent progress. *Proc. Instn. Mech. Engrs.*, **205**, 39-52.

Ni, S. H., Z. Y. Feng, and P. S. Tsai (1994) Analysis of the vibration response and screening effectiveness of strip foundation. *J. Chinese Inst. Civil and Hydraulic Eng*. (in Chinese), **6**(3), 269-277.

Okumura, Y. and K. Kuno (1991) Statistical analysis of field data of railway noise and vibration collected in an urban area. *Appl. Acoustics*, **33**, 263-280.

Payton, R. G. (1967) Transient motion of an elastic half-space due to a moving surface line load. *Int. J. Eng. Sci*., **5**, 49-79.

Schmid, G., N. Chouw, and R. Le (1991) Shielding of structures from soil vibrations. *Soil Dyn. Earthquake Eng. V, Int. Conf. Soil Dyn. & Earthquake Eng*., pp. 651-662, Computational Mechanics Publications, Southampton, U.K.

Segol, G., C. Y. Lee, and J. F. Abel (1978) Amplitude reduction of surface waves by trenches. *J. Eng. Mech. Div*., ASCE, **104**(EM3), 621-641.

Sneddon, I. N. (1951) *Fourier Transforms*. McGraw-Hill, New York, NY, U.S.A.

Suiker, A. S. J., R. de Borst, and C. Esveld (1998) Critical behaviour of a Timoshenko beam-half plane system under a moving load. *Archive*

Appl. Mech., **68**, 158-168.

Takemiya, H. (1997) Prediction of ground vibration induced by high-speed train operation. *18th Sino-Japan Technology Seminar*, pp. 1-10, Chinese Inst. of Engineers, Taipei, Taiwan, R.O.C.

Takemiya, H. (1998a) Lineside ground vibrations induced by high-speed train passage. *Workshop on Effect of High-Speed Vibration on Structures and Equipment*, pp. 43-49, Dept. Civil Eng., Nat. Cheng Kung Univ., Tainan, Taiwan, R.O.C.

Takemiya, H. (1998b) Paraseismic behavior of wave impeding block measured for ground vibration reduction. *Workshop on Effect of High-Speed Vibration on Structures and Equipment*, pp. 51-56, Dept. Civil Eng., Nat. Cheng Kung Univ., Tainan, Taiwan, R.O.C.

Takemiya, H. and A. Fujiwara (1994) Wave propagation/impediment in a stratum and wave impeding block (WIB) measured for SSI response reduction. *Soil Dyn. Earthquake Eng.*, **13**, 49-61.

Thiede, R. and H. G. Natke (1991) The influence of thickness variation of subway walls on the vibration emission generated by subway traffic. *Soil Dyn. Earthquake Eng., V: Int. Conf. Soil Dyn. & Earthquake Eng.*, pp. 673-682, Computational Mechanics Publications, Southampton, U.K.

Trochides, A. (1991) Ground-borne vibrations in buildings near subways. *Appl. Acoustics*, **32**, 289-296.

Verhas, H. P. (1979) Prediction of the propagation of train-induced ground vibration. *J. Sound Vibr.*, **66**(3), 371-376.

Wilson, G. P., H. J. Saurenman, and J. T. Nelson (1983) Control of ground-borne noise and vibration. *J. Sound. Vibr.*, **87**(2), 339-350.

Wolf, J. P. (1985) *Dynamic Soil-Structure Interaction*. Prentice-Hall, Englewood Cliffs, NJ, U.S.A.

Wolf, J. P. and C. Song (1996) *Finite-Element Modeling of Unbounded Media*. John Wiley & Sons, New York, NY, U.S.A.

Woods, R. D. (1968) Screening of surface waves in soils. *J. Soil Mech. Found. Div.*, ASCE, **SM4**, 951-979.

Yang, Y. B. and H. H. Hung (1997) A parametric study of wave barriers for reduction of train-induced vibrations. *Int. J. Num. Meth. Eng.*, **40**, 3729-3747.

Yang, Y. B., S. R. Kuo, and H. H. Hung (1996) Frequency-independent infinite element for analyzing semi-infinite problems. *Int. J. Num. Meth. Eng.*, **39**, 3553-3569.

Yeh, C. S., W. I. Liao, J. F. Tsai, and T. J. Teng (1997) *Train Induced Ground Motion and Its Mitigation by Trench and WIB* (in Chinese). Report of NCREE-97-009, Nat. Center for Research on Earthquake Eng., Taipei, Taiwan, R.O.C.

列車引致之土壤振動問題之文獻回顧

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摘　要

在本文中，將針對因列車移動所引致之土壤波傳效應作相關文獻回顧。歷史上，相關的問題曾以不同的分析方法探討，包括理論與解析模式，現場測量，經驗公式以及數值模擬。文中將針對此四類分別作相關文獻的探討與回顧，最後並對文獻上曾建議或採用過之隔震模式加以評述。