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by

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Ground Vibration Boom from High-Speed Trains

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ABSTRACT

A brief review is given of the recent theoretical investigations into generation of ground vibrations by high-speed trains carried out at the Nottingham Trent University. One of the most interesting results of these investigations was the prediction of a ground vibration boom from high-speed trains which may occur when train speeds exceed the velocity of Rayleigh surface waves in the ground. The existence of a ground vibration boom has been recently confirmed experimentally on the newly opened high-speed railway line in Sweden for train speeds of only 160 km/h. The observed very large increase of generated ground vibrations implies that this phenomenon should be taken into account by designers and operators of high-speed railways.

1. INTRODUCTION

During the last decade Railways have become one of the most advanced and fast developing branches of transportation technology, comparable with the space technology in breakthrough of the 1960s (Banister and Hall 1994; Streeter 1994; Ford and Smith 1995). The reason is the high speed achievable by the most advanced modern trains (French TGV, Eurostar, German ICE, etc.) and very low air pollution per passenger compared with road vehicles. All these make railways competitive with air and road transport at medium distances, which are typical for European travel. Prospective plans for the year 2010 assume that the New European Trunk Line will have connected Paris, London, Brussels, Amsterdam, Cologne and Frankfurt by a high-speed railway service that will provide fast and more convenient passenger communications within Europe.

Unfortunately, the increased speeds of modern trains are normally accompanied by increased levels of associated noise and ground vibrations that are significant even for conventional railways. These vibrations, being predominantly of low-frequency range, may cause structural dynamic movements of nearby buildings at their resonance frequencies and result in disamenity, both directly and by generating structure-borne noise.

Although a number of experimental and theoretical investigations of railway-generated ground vibrations have been carried out for conventional passenger and heavy-freight trains travelling both above- and underground (Remington et al. 1987; Melke 1988; Newland et al. 1991), very little has been done so far with regard to vibrations from high-speed trains. The first theoretical investigations of such kind have been carried out by the present

author (see, e.g., Krylov 1994, 1995a, 1996, 1997, 1998). These contributed to understanding the reasons why an increase in train speeds is accompanied by higher levels of generated ground vibrations. Also, it has been predicted during these investigations that especially large increase in vibration level should take place if train speeds v exceed the velocity of Rayleigh surface waves in the ground c_R . In other words, if the number $K = v/c_R$ is larger than one. If this happens, a ground vibration boom takes place, similar to a sonic boom described by the Austrian physicist E. Mach about a century ago.

Note that it took more than 50 years between the publication of E. Mach's investigation and the appearance of first supersonic jets generating a sonic boom. The distance from the first theoretical prediction of a ground vibration boom from high-speed trains (Krylov 1994) to its practical realisation was much shorter. As was reported by Dr C. Madshus at the recent conference "*Ground Dynamics and Man-made Processes: Prediction, Design, Measurement*" (ICE, London, 20 November 1997), in October 1997 a research team from the Norwegian Geotechnical Institute observed for the first time the severe ground motions when train speeds exceeded the Rayleigh wave velocity in the supporting ground. The problem was experienced by the Swedish Railway Authorities (Banverket) when their West-coast Main Line from Gothenburg to Malmö was opened for the X2000 high-speed train (Madshus 1997). The speeds achievable by the X200 train (up to 200 km/h) can be larger than Rayleigh wave velocities in this part of South-Western Sweden characterised by very soft ground. In particular, at the location near Ledsgård the Rayleigh wave velocity in the ground was as low as 45 m/s, so that the increase in train speed from 140 to 180 km/h lead to about 10 times increase in generated ground vibration level.

Vibration measurements on the railway embankment at the same location showed that "for train speeds around 200 km/h the dynamic motion of the railway embankment was severe, with peak acceleration near 10 m/s² and peak to peak deflection in the order to 15 to 20 mm". Clearly, such an increase in generated ground vibrations may cause noticeable movements and even structural damage of nearby buildings, let alone the annoyance due to building vibration and structure-borne noise.

The above mentioned first observations of a ground vibration boom in South-Western Sweden indicate that the era of "supersonic" or (more precisely) "trans-Rayleigh" trains has begun. In the present paper, we give a brief description of the theory of generating ground vibration boom by high-speed trains and illustrate the discussion by the numerical calculations of ground vibrations generated by TGV or Eurostar high-speed trains. Finally, we compare our theoretical calculations with the experimental observations made in Sweden.

2. THEORETICAL BACKGROUND

2.1 Mechanisms of generating ground vibrations

Let us assume that a train has N carriages and moves at speed v on a welded track with sleeper periodicity d . As has been demonstrated experimentally by a number of researchers, there are several mechanisms of generating ground vibrations which may contribute to the total ground vibration level in different frequency bands. Among these mechanisms one can mention the wheel-axle pressure onto the track, the effects of joints in unwelded rails, the unevenness of wheels or rails (all these mechanisms cause vibrations at trainspeed-

dependent frequencies), and the dynamically induced forces of carriage- and wheel-axle vibrations excited mainly by unevenness of wheels and rails (these occur at their natural frequencies).

2.2 Wheel-axle pressure generation mechanism

Among the above mentioned mechanisms the most common and the most important one is a quasi-static pressure of wheel axles onto the track which, as will be demonstrated below, is responsible also for railway-generated ground vibration boom. An essential aspect of analysing the above mentioned wheel-axle pressure generation mechanism is calculation of the track deflection curve as function of the applied axle load. One can treat a track as an Euler – Bernoulli elastic beam of uniform mass m_0 lying on a visco-elastic half space $z > 0$ and use the following dynamic equation to describe its vertical deflections (see, e.g., Fryba 1973):

$$EI \partial^4 w / \partial x^4 + m_0 \partial^2 w / \partial t^2 + \alpha w = T \delta(x-vt) \quad (1)$$

Here w is the beam deflection magnitude, E and I are Young's modulus and the cross-sectional momentum of the beam, α is the proportionality coefficient of the equivalent Winkler elastic foundation, x is the distance along the beam, T is a vertical point force, v is its speed, and $\delta(x)$ is the Dirac's delta-function. The solution of (1) has the form

$$w(x-vt) = (T/8EI\beta^3\delta) \exp(-\beta\delta |x-vt|) [\cos(\beta\eta(x-vt) + (\delta\eta)\sin(\beta\eta |x-vt|))], \quad (2)$$

where $\beta = (\alpha/4EI)^{1/4}$, $\delta = (1-v^2/c_{min}^2)^{1/2}$ and $\eta = (1+v^2/c_{min}^2)^{1/2}$; the term $c_{min} = (4\alpha EI/m_0^2)^{1/4}$ represents the minimal phase velocity of bending waves propagating in a system track/ground. To calculate forces applied from sleepers to the ground, e.g., for a sleeper located at $x = 0$, one should substitute eqn (2) into the following expression:

$$P(t) = T[2w(vt)/w_{max}^{st}](d/x_0^{st}) \quad (3)$$

where d is a sleeper periodicity, index “st” corresponds to the quasi-static solution of eqn (1), i.e., for $m_0 \partial^2 w / \partial t^2 = 0$. In particular, w_{max}^{st} is the maximal value of $w(vt)$ in quasi-static approximation, and $x_0^{st} = \pi\beta$ is the effective quasi-static track deflection distance. As one can see, for relatively low train speeds, i.e., for $v \ll c_{min}$, the value of δ is close to 1, so that the dynamic solution goes over to the quasi-static one. For typical parameters of track and ballast, c_{min} is essentially larger than even the highest known train speed ($v = 515 \text{ km/h}$). Note, however, that for very soft soils c_{min} may be as low as 50-100 m/s which is comparable with speeds of modern high-speed trains. Since the parameter $\delta = (1 - v^2/c_{min}^2)^{1/2}$ is present in the denominator of the proportionality factor $T/EI\beta^3\delta$ in eqn (2), the track deflections and the associated dynamic forces applied from sleepers to the ground increase as the train speed approaches the minimal track wave velocity. This may result in the increase in magnitudes of generated ground vibrations at these train speeds (Krylov 1996, 1997, 1998).

Note that possible large rail deflections at train speeds approaching track critical velocity may result even in train derailling, thus representing a serious

problem also from the point of view of train and passenger safety. Different aspects of this problem are now widely investigated in the UK and Worldwide (see, e.g., Heelis et al. 1998, 1999).

2.3 Green's function

The next step in developing the theory is derivation of the Green's function for the problem under consideration. The physical meaning of such a Green's function is that it describes ground vibrations generated by an individual sleeper which in a good approximation can be regarded as a point source in the low-frequency band typical for recorded railway-generated ground vibration signals. We recall that for homogeneous elastic half space the corresponding Green's function can be derived using the results of the well-known axisymmetric Lamb's problem for the excitation by a vertical point force applied to the surface (see, e.g., Ewing et al. 1957). The solution of this problem, which should satisfy the dynamic equations of elasticity for a homogeneous medium subject to the stress-free boundary conditions on the surface, gives the corresponding components of the dynamic Green's tensor (or, for simplicity, the Green's function) G_{zi} for an elastic half space. For the problem under consideration, only Rayleigh surface wave contribution (the Rayleigh part of the Green's function) can be considered since Rayleigh waves transfer most of the vibration energy to remote locations. For these waves the spectral density of the vertical velocity component of ground vibrations generated by one sleeper at the surface of homogeneous half space ($z=0$) is proportional to $P(\omega)(1/\rho) \exp(ik_R \rho - \gamma k_R \rho)$, where $P(\omega)$ is a Fourier transform of the force $P(t)$ applied from a sleeper to the ground, ρ is the distance between the source (sleeper) and the point of observation on the ground surface, $\omega = 2\pi F$ is a circular frequency, $k_R = \omega/c_R$ is the wavenumber of a Rayleigh surface wave, c_R is the Rayleigh wave velocity, and $\gamma = 0.001 - 0.1$ is an empirical constant describing the "strength" of dissipation of Rayleigh waves in soil (Gutovski & Dym 1976).

To consider the influence of layered geological structure of the ground on generating ground vibrations, one would have to use the Green's function for a layered elastic half space, instead of that for a homogeneous half space. As a rule, such a function, that contains information about the total complex elastic field generated in a layered half space considered (including different modes of surface waves and modes radiating energy into the bulk (leaky waves)), can not be obtained analytically (see, e.g., Jones & Petyt 1993). However, for the purpose of description of railway-generated ground vibrations, the situation can be simplified by using an approximate engineering approach to the construction of a Green's function which takes into account the effects of layered structure on the amplitude and phase velocity of only the lowest order surface mode which goes over to a Rayleigh wave at higher frequencies (Krylov 1997). The propagating modes of higher order and leaky modes are generated less effectively by surface forces associated with sleepers and can be disregarded.

For simplicity, we also assume that the Poisson ratio σ of the layered ground and the mass density ρ_0 are constant. The corresponding approximate expression for the Green's function component $G_{zz}^L(\rho, \omega)$ describing the effect of a layered structure on generated vertical component of ground vibration velocity has the form (Krylov 1997):

$$G_{zz}^L(\rho, \omega) = D^L(\omega)(1/\rho) \exp(ik_R^L \rho - \gamma k_R^L \rho), \quad (4)$$

$$D^L(\omega) = (\pi/2)^{1/2}(-i\omega)q^L(k_R^L)^{1/2}(k_t^L)^2 \exp(-i3\pi/4)/\mu^L(\omega)F_L'(k_R^L) \quad (5)$$

Here $\rho = [(x-x')^2 + (y-y')^2]^{1/2}$ is the distance between the source (with current coordinates x', y') and the point of observation (with coordinates x, y), $\omega = 2\pi F$ is a circular frequency, $k_R^L = \omega/c_R(\omega)$ is the wavenumber of a lowest order Rayleigh mode propagating with frequency-dependent velocity $c_R(\omega)$; terms $k_t^L = \omega/c_t^L(\omega)$ and $k_l^L = \omega/c_l^L(\omega)$ are “effective” wavenumbers of longitudinal and shear bulk elastic waves at given frequency ω . In the model under consideration, the “effective” longitudinal $c_l^L(\omega)$ and shear $c_t^L(\omega)$ wave velocities as well as the corresponding “effective” shear modulus $\mu^L(\omega)$ are expressed in terms of frequency-dependent Rayleigh wave velocity $c_R(\omega)$ using the well known relations:

$$c_R(\omega)/c_t^L(\omega) = (0.87 + 1.12\sigma)/(1 + \sigma), \quad (6)$$

$$c_l^L(\omega)/c_t^L(\omega) = [(1 - 2\sigma)/2(1 - \sigma)]^{1/2}, \quad (7)$$

$$\mu^L(\omega) = \rho_0[c_t^L(\omega)]^2. \quad (8)$$

The term q^L is defined as $q^L = [(k_R^L)^2 - (k_t^L)^2]^{1/2}$ and the factor $F_L'(k_R^L)$ is determined according to the following relationship (Biryukov et al. 1995):

$$F_L'(k_R^L) = N(\sigma)(k_R^L)^3 \quad (9)$$

where $N(\sigma)$ is a dimensionless function of the Poisson ratio σ (e.g., for $\sigma = 0.25$, the function $N(\sigma)$ takes the value -2.3).

The dependence of Rayleigh wave velocity on frequency, $c_R(\omega)$, is determined by the particular profile of layered ground, characterised by the dependence of its elastic moduli λ, μ and mass density ρ_0 on vertical coordinate z . For all ground profiles the determination of the velocity $c_R(\omega)$ is a complex boundary-value problem which, generally speaking, requires numerical calculations.

2.4 Calculation of ground vibrations from moving trains

To calculate ground vibrations generated by a train one needs superposition of waves generated by each sleeper activated by wheel axles of all carriages, with the time and space differences between sources (activated sleepers) being taken into account. Using the Green's function this may be written in the form (Krylov & Ferguson, 1994; Krylov 1995a)

$$v_z(x, y, \omega) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(x', y', \omega) G_{zz}^L(\rho, \omega) dx' dy', \quad (10)$$

where $P(x', y', \omega)$ describes the space distribution of all load forces acting along the track in the frequency domain. This distribution can be found by taking a Fourier transform of the time and space dependent load forces $P(t, x', y'=0)$ applied from the track to the ground. For all sleepers, axles and carriages being taken into account this function has a form

$$P(t, x', y'=0) = \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} A_n [P(t-(x'+nL)/v) + P(t-(x'+M+nL)/v)] \delta(x'-md) \delta(y'), \quad (11)$$

where $\rho_m = [y_0^2 + (md)^2]^{1/2}$, N is the number of carriages, M is the distance between the centres of bogies in each carriage and L is the total carriage length. Dimensionless quantity A_n is an amplitude weight-factor to account for different carriage masses (for simplicity we assume all carriage masses to be equal, i.e., $A_n = 1$).

Eqns (10), (11) and (2) – (9) result in the following expression for the frequency spectra of vertical vibrations at $z=0$, $x = 0$ and $y = y_0$ generated by a moving train:

$$v_z(0, y_0, \omega) = P(\omega) D^L(\omega) \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} [\exp(-\gamma \omega \rho_m / c_R(\omega)) \sqrt{\rho_m} [1 + \exp(iM\omega/v)] \exp(i(\omega/v)(md + nL) + i(\omega/c_R(\omega))\rho_m)] \quad (12)$$

Note that the eq (12) is applicable for trains moving at arbitrary speeds.

2.5 Trans-Rayleigh trains

For “trans-Rayleigh trains”, i.e., trains travelling at speeds higher than Rayleigh wave velocity in the ground, it follows from (12) that maximum radiation of ground vibrations (a ground vibration boom) takes place if the train speed v and Rayleigh wave velocity $c_R(\omega)$ satisfy the relation

$$\cos\Theta = 1/K = c_R(\omega)/v \quad (13)$$

where Θ is the observation angle. Since the observation angle Θ must be real ($\cos\Theta \leq 1$), the value of $K = v/c_R(\omega)$ should be larger than 1, i.e., the train speed v should be larger than Rayleigh wave velocity $c_R(\omega)$. Under this condition, ground vibrations are generated as quasi-plane Rayleigh surface waves symmetrically propagating at angles Θ with respect to the track, and with amplitudes much larger than those for “sub-Rayleigh trains”.

3. CALCULATIONS OF RAILWAY-GENERATED VIBRATIONS

3.1 Ground vibrations from complete high-speed trains

Ground vibration frequency spectra generated by complete TGV or Eurostar trains travelling on homogeneous or inhomogeneous ground for both sub-Rayleigh and trans-Rayleigh train speeds (e.g., for $v = 50$ km/h and $v = 500$ km/h) can be calculated using eqn (12) for a limited number of sleepers being taken into account ($m = -150 \dots 150$). It is normally assumed in such calculations that typical train consists of $N=5$ equal carriages with the parameters $L = 18.9$ m and $M = 15.9$ m. Since the bogies of TGV and Eurostar trains have a wheel spacing of 3 m and are placed between carriage ends, i.e., they are shared between two neighbouring carriages, one should consider each carriage as having one-axle bogies separated by the distance $M = 15.9$ m. Other typical parameters are: $T = 100$ kN, $\gamma = 0.05$, $\beta = 1.28$ m⁻¹, $y_0 = 30$ m, where y_0 is the distance from the track to the observation point, and $c_R = 125$ m/s.

The results of the calculations show (Krylov 1995a, 1996, 1997, 1998) that for homogeneous ground the averaged ground vibration level from a train moving at trans-Rayleigh speed 500 km/h (138.8 m/s) is approximately 70 dB higher than from a train travelling at speed 50 km/h (13.8 m/s).

Including the effect of layered ground, results in decrease of ground vibration level from a trans-Rayleigh train at low frequencies (Krylov 1997). Note, that for trains travelling at low speeds the effect of layered ground is small

(the corresponding curves are almost indistinguishable).

It is important to consider the effect of train speed v on the amplitude of 1/3-octave spectral component of ground vibrations generated by a TGV or Eurostar train at the central frequency of 25 Hz (Krylov 1998). Figure 1 shows the corresponding amplitude (in dB, relative to the reference level of 10^{-9} m/s) for speeds not exceeding the Rayleigh wave velocity ($c_R = 125$ m/s in the case considered). One can see that, in agreement with practical observations, the averaged level of vibrations increases with the increase of v . The sharp peak around $v = 1.75$ m/s relates to the sleeper passage condition $f_p = v/d$.

3.2 Effect of sleepers on generated ground vibrations

Another important conclusion following from the analysis of ground vibrations generated by high-speed trains is that radiation of ground vibrations by trans-Rayleigh trains may take place also on tracks without sleepers (Krylov 1995a, 1998). However, for conventional low-speed trains ($v < c_R$), ground vibrations in the form of waves are almost not generated on tracks without sleepers in the framework of the quasi-static generation mechanism considered. This agrees with the well known result of the elasticity theory that, for loads moving along a free surface of an elastic half space at speed $v < c_R$, radiated wave-fields do not exist (only localised quasi-static fields can accompany the moving load). Thus, the presence of sleepers is essential for generated ground vibrations by conventional trains due to the mechanism of wheel-axle pressure considered here. Changes of d to smaller values may result in noticeable reduction in high-frequency components of generated ground vibration spectra (Krylov 1998). In the case of conventional trains, this effect may be used as a mitigation measure to protect the built environment in selected parts of the existing railway route. However, for trans-Rayleigh trains this method is not effective and alternative mitigation methods should be used.

3.3. Effect of other generation mechanisms

On tracks with rough surfaces or on unwelded tracks the predicted ground vibration spectra may differ from experimentally observed ones because the wheel-axle pressure generation mechanism may not dominate at conventional train speeds. Therefore, if other generation mechanisms mentioned earlier are essential, the expected 70 dB averaged increase of ground vibration level in the above mentioned example should be reduced roughly to $(70 - I)$ dB, where $I = 20 \log(A_{oth}/A_{wp})$ determines the relation (in dB) between the ground vibration amplitudes due to the wheel-pressure mechanism (A_{wp}) and other (A_{oth}) mechanisms of generation.

3.4 Effect of bulk elastic waves

In this section we briefly discuss possible influence of bulk shear and compressive elastic waves (S- and P-waves), radiating into the bulk of the ground, on the total level of ground vibrations generated by high-speed trains. Obviously, radiated S- and P-waves can also be significantly amplified if train speeds are high enough and the conditions $v < c_t$ or even $v < c_l$ hold, in addition to the trans-Rayleigh condition $v > c_R$ considered above (we recall that $c_R < c_t < c_l$). In such cases these waves will be radiated into the ground as conical ground vibration booms propagating at the angles $\Theta_t = \arccos(c_t/v)$ and $\Theta_l = \arccos(c_l/v)$ relative to the track, in addition to the ground vibration boom associated with Rayleigh waves radiated as quasi-plane waves along the surface at the angles $\Theta = \arccos(c_R/v)$ relative to the track. The most likely contribution

to the total ground vibration boom might be that of radiated S- waves since their velocity c_p , being only about 10% higher than the velocity of Rayleigh waves, can be easier achieved by moving trains than the velocity of compressive waves c_l . Especially important the contribution of shear-wave-associated ground vibration boom may be for high-speed underground trains for which the role of bulk shear waves is often more essential than that of Rayleigh waves (Krylov, 1995b).

Figure 1. Effect of train speed v on the amplitude of 1/3-octave spectral component of ground vibrations generated by TGV trains at the central frequency of 25 Hz for speeds not exceeding the Rayleigh wave velocity in the upper ground layer ($c_2 = 125$ m/s in the case considered)

3.5 Waveguide effects of the railway embankments

An important aspect which should be considered in design of high-speed railway lines is possible waveguide effects of the embankment (if the latter is present) on ground vibration boom from high-speed trains. The possibility of the embankments acting as waveguides for railway-generated ground vibrations was at first mentioned in the paper of the present author (Krylov 1995a) where it was emphasised that Rayleigh waves associated with a ground vibration boom are usually radiated at small angles Θ relative to the track. Under such circumstances, if a track is placed on the top of the embankment, a dominant part of the radiated energy is expected to be trapped and dissipated within the embankment itself, without significant leakage to the area outside. The physical principle of such waveguides, that can be called "topographic waveguides", has been described in the earlier publications of the present author interpreting the

existence of guided (trapped) modes in such waveguides in terms of total internal reflections of surface waves from the geometric boundaries between the embankment's top flat and side slope surfaces (see, e.g., Biryukov et al. 1995).

A preliminary indication of the presence of such waveguide effects for real railway embankments follows from the experiments carried out by the Norwegian Geotechnical Institute on the line from Gothenburg to Malmö (Madshus 1997). Vibration measurements on the railway embankment itself showed that for train speeds around 200 km/h particle acceleration of the railway embankment was near 10 m/s^2 and peak to peak deflection achieved 20 mm (see the Introduction). However, further theoretical and experimental research is needed to investigate these important phenomena in more detail.

3.6 Comparison of the theory with the recent experiments in Sweden

It is important to compare the above described theory with the recent observations made by the team from the Norwegian Geotechnical Institute on the railway line from Gothenburg to Malmö (see the Introduction). Since no detailed experimental data are available at the moment, we calculate the ground vibration velocity averaged over the frequency range 0-50 Hz and use the reported low value of Rayleigh wave velocity in the ground ($c_R = 45 \text{ m/s}$), assuming that the Poisson ratio of the ground σ is 0.25. To facilitate the comparison of the predicted increase in ground vibration level with the observed one we calculate the amplitudes of ground vibrations in linear units (m/s).

Figure 2. Effect of train speed v on the amplitude of ground vibration velocity averaged over the frequency range 0-50 Hz (in m/s) generated by TGV trains on the ground with the Rayleigh wave velocity $c_R = 45 \text{ m/s}$

The resulting amplitude as a function of train speed is shown on Figure 2. One can see that the predicted amplitudes of vertical velocity component of generated ground vibrations change from $2 \cdot 10^{-5}$ m/s at $v = 140$ km/h (38.8 m/s; see vertical mark "*" on Figure 2) to $16 \cdot 10^{-5}$ m/s at $v = 180$ km/h (50 m/s; see vertical mark "***" on figure 2). Thus, the estimated 8 times increase in ground vibration level following from the above theory for the considered train speeds and Rayleigh wave velocity is in reasonable agreement with the 10 times increase recently observed experimentally for the Swedish high-speed railway line built on the soft ground (Madshus, 1997).

CONCLUSIONS

The above described theory of generating ground vibrations by high-speed trains shows that if train speeds exceed the velocity of Rayleigh surface waves in the supporting soil a ground vibration boom occurs associated with very large increase in amplitudes of generated vibrations.

Recent first experimental observations of a ground vibration boom made by the Norwegian Geotechnical Institute for Swedish X2000 trains travelling at speeds of 140-180 km/h on the line built on soft soil confirms the predictions of the theory. This implies that a railway-generated ground vibration boom is no longer an exotic theoretical effect with uncertain applications in the future. It is a today's reality for high-speed railway lines crossing soft soils, and so are "supersonic" or "trans-Rayleigh" trains.

The builders and operators of high-speed railways must be aware of possible consequences of a ground vibration boom. The direct relevance of this phenomenon in the UK is to the construction of the Channel Tunnel Rail Link, especially on those parts of the routes where high-speed railway lines pass across soft alluvial soils, such as Rainham Marshes, etc. Like in South-Western Sweden, Rayleigh wave velocities on such sites can be as low as 40-50 m/s, so that a ground vibration boom can be expected for relatively low train speeds. One can expect that similar problems will arise also on some sites of other high speed lines both in the UK and abroad, especially in the Netherlands with its very soft soils.

It is too early on this stage to foresee how the phenomenon of railway-generated ground vibration boom will be reflected in future standards on noise and vibration from high-speed trains. However, one can expect that such important parameter as Rayleigh wave velocity in the ground for the sites considered will be present in all these standards indicating maximal train speeds beyond which excessive ground vibrations can be expected. Using this information, one will have either to avoid very high train speeds on the sites concerned or to undertake necessary remediation measures.

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