Rail movement and ground waves caused by high-speed trains approaching track–soil critical velocities

V V Krylov1, A R Dawson2, M E Heelis2 and A C Collop2
1Department of Civil and Structural Engineering, The Nottingham Trent University, Nottingham, UK
2School of Civil Engineering, University of Nottingham, UK

Abstract: The increased speeds of modern trains are normally accompanied with increased transient movements of the rail and ground, which are especially high when train speeds approach some critical wave velocities in the track–ground system. These transient movements may cause large rail deflections, as well as structural vibrations and associated noise in nearby buildings. There are two main critical wave velocities in the track–ground system: the velocity of the Rayleigh surface wave in the ground and the minimum phase velocity of bending waves propagating in the track supported by ballast, the latter velocity being referred to as the track critical velocity. Both these velocities can be exceeded by modern high-speed trains, especially in the case of very soft soil where both critical velocities become very low. The discussion in this paper focuses on the effects of transient rail deflections on associated ground vibrations in the cases of train speeds approaching and exceeding Rayleigh wave and track critical velocities. The obtained theoretical results are illustrated by numerical calculations for TGV and Eurostar high-speed trains travelling along typical tracks built on soft soil.

Keywords: high-speed trains, rail dynamics, critical velocities, ground vibration boom

NOTATION

\( c_l \) longitudinal wave velocity in the ground
\( c_{\text{min}} \) track critical velocity
\( c_R \) Rayleigh wave velocity in the ground
\( c_t \) shear wave velocity in the ground
\( d \) sleeper periodicity
\( E \) Young’s modulus of the rail
\( G_{zz} \) Green’s function
\( I \) cross-sectional momentum of the rail
\( k_l \) wave number of longitudinal bulk elastic waves in the ground
\( k_R \) wave number of Rayleigh waves in the ground
\( k_t \) wave number of shear bulk elastic waves in the ground
\( L \) total carriage length
\( m_0 \) uniform mass of the rail
\( M \) distance between the centres of bogies in each carriage
\( N \) number of carriages
\( T \) wheel-axle load

\( v \) train speed
\( w \) track deflection magnitude
\( x \) distance along the beam
\( \alpha \) stiffness of the equivalent Winkler foundation
\( \gamma \) dissipation constant of Rayleigh waves in the ground
\( \delta(x) \) Dirac delta function
(\( \theta \)) observation angle
\( \mu \) shear modulus of the ground
\( \rho \) distance between a source and the point of observation
\( \omega \) circular frequency
\( \omega_b \) circular frequency of damping
\( \omega_{tb} \) track on ballast resonance frequency

1 INTRODUCTION

During the last decade, high-speed railways have become one of the most advanced and fast developing branches of transport [1, 2]. The reason is relatively low air pollution per passenger compared with road vehicles and very high speeds achievable by the most advanced modern trains—French TGV, Japanese Shinkansen, German ICE, Italian Pendolino, Swedish X2000, Spanish AVE, the Thalys and
the Eurostar. All these make railways competitive with air and road transport at medium distances which are typical for European travel [3]. Prospective plans for the year 2010 assume that the New European Trunk Line will have connected Paris, London, Brussels, Amsterdam, Cologne and Frankfurt by high-speed railway services that will provide fast and more convenient passenger communications within Europe.

Unfortunately, the increased speeds of modern trains are normally accompanied with increased transient movements of the rail and ground, which may cause noticeable vibrations and structure-borne noise in nearby buildings [4, 5]. For modern high-speed trains these transient movements are especially high when train speeds approach certain critical wave velocities in the track-ground system. There are two main critical wave velocities in the track-ground system: the velocity of the Rayleigh surface wave in the ground and the minimum phase velocity of bending waves propagating in the track supported by ballast, the latter velocity being referred to as the track critical velocity. Both these velocities can easily be exceeded by modern high-speed trains, especially in the case of very soft soil where both critical velocities become very low.

As has been theoretically predicted by one of the authors [6, 7], if a train speed \( v \) exceeds the Rayleigh wave velocity \( c_R \) in supporting soil, then a ground vibration boom occurs which is associated with a very large increase in generated ground vibrations, as compared with the case of conventional trains. This phenomenon is similar to a sonic boom for aircraft crossing the sound barrier, and its existence has been recently confirmed experimentally [8]. The measurements have been carried out on behalf of the Swedish Railway Authorities when their West-coast Main Line from Gothenburg to Malmö was opened for the X2000 high-speed train. The speeds achievable by the X2000 train (up to 200 km/h) can be larger than Rayleigh wave velocities in this part of South-Western Sweden, which is characterized by very soft ground (see also reference [9]). In particular, at a 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 led to an increase by a factor of about 10 in the generated ground vibration level [8]. The above-mentioned first observations of a ground vibration boom indicate that it is now possible to speak about "supersonic" or (more precisely) "trans-Rayleigh" trains [10–12]. The increased attention of local authorities and railway companies to ground vibrations associated with high-speed trains has stimulated a growing number of theoretical and experimental investigations in this area (see, for example, references [13] to [16]).

If train speeds increase further and approach the track critical velocity, then rail deflections due to applied axle loads become especially large. Possible very large rail deflections at this speed may even result in train derailment, thus representing a serious problem for train and passenger safety [9, 17–19]. From the point of view of generated ground vibrations, these large rail deflections can be responsible for an additional growth in ground vibration amplitudes, as compared with the above-mentioned case of ground vibration boom. Investigations of this effect have been carried out for train speeds not exceeding the track critical velocity, so that it was possible to make all calculations without taking into account track wave dissipation [10, 12].

In the present paper, the effects of transient rail deflections on amplitudes of generated ground vibrations are considered for the cases of train speeds approaching and exceeding both Rayleigh wave and track wave critical velocities. Under such circumstances, the effect of track wave dissipation is paramount, being a limiting factor for the amplitudes of rail deflections at train speeds equal to and higher than the track critical velocity. The obtained theoretical results are illustrated by numerical calculations for TGV and Eurostar high-speed trains travelling along typical tracks built on soft soil.

2 THEORETICAL BACKGROUND

2.1 Mechanisms of generating ground vibrations

In what follows, an idealized model of a train consisting of \( N \) carriages is considered. It is assumed that the train is travelling at speed \( v \) along a track with sleeper periodicity \( d \) (Fig. 1a). It is possible to distinguish several mechanisms of railway-generated ground vibrations that may contribute to the total ground vibration level in different frequency bands. These mechanisms include the wheel-axle pressure on the track, the effects of joints in unwelded rails, the unevenness of wheels or rails, and the dynamically induced forces of carriage and wheel-axis vibrations excited mainly by unevenness of wheels and rails. Among the above-mentioned mechanisms, only the most common one, which is present even for ideally flat rails and wheels, is considered—the quasi-static pressure of wheel axles on the track.

![Fig. 1](image-url) (a) Geometry of track and train and (b) the wheel-axle pressure mechanism of generating ground vibrations
(Fig. 1b). As will be demonstrated below, this mechanism is also responsible for railway-generated ground vibration boom. The role of other generation mechanisms is discussed elsewhere [12].

2.2 Track dynamic properties

An essential aspect of analysing the above-mentioned wheel-axle pressure generation mechanism is calculation of the track deflection curve as a function of the applied axle load and train speed. Each rail can be treated as a Euler–Bernoulli elastic beam of uniform mass \( m_0 \) lying on a viscoelastic half-space \( z > 0 \), and the following dynamic equation can be used to describe its vertical deflections (see, for example, reference [20]):

\[
EI \frac{\partial^4 w}{\partial x^4} + m_0 \frac{\partial^2 w}{\partial t^2} + 2m_0 \omega_0 \frac{\partial w}{\partial t} + \alpha w = T \delta(x-\nu t) \tag{1}
\]

where \( w \) is the beam deflection magnitude, \( E \) and \( I \) are Young’s modulus and the cross-sectional momentum of the beam, \( \omega_0 \) is the circular frequency of damping, \( \alpha \) is the proportionality coefficient of the equivalent Winkler elastic foundation, \( x \) is the distance along the beam, \( T \) is the wheel-axle load considered as a vertical point force, \( \nu \) is its speed and \( \delta(x) \) is the Dirac delta function.

It is useful firstly to discuss free wave propagation in the supported beam without damping, i.e. to analyse equation (1) with \( T = 0 \) and \( \omega_0 = 0 \). In this case, the substitution of the solution in the form of harmonic bending waves

\[
w = A \exp (ikx - i\omega t) \tag{2}
\]

in equation (1) gives the following dispersion equation for track waves propagating in the system:

\[
\omega = \frac{(\alpha + EI k^2)^{1/2}}{m_0^{1/2}} \tag{3}
\]

where \( k \) is the wave number of track waves and \( \omega \) is the circular frequency. In the quasi-static (long-wave) approximation \( (k = 0) \), dispersion equation (3) reduces to the well-known expression for the so-called track on ballast foundation:

\[
\omega = \frac{\alpha^{1/2}}{m_0^{1/2}}. \tag{4}
\]

For example, typical parameters \( \alpha = 52.6 \text{ MN/m}^2 \) [21] and \( m_0 = 300 \text{ kg/m} \), this gives \( F_{ib} = \omega_0/(2\pi) = 67 \text{ Hz} \). The frequency \( F_{ib} \) represents the minimum frequency of propagating track waves. It also follows from equation (3) that the frequency dependent velocity of track wave propagation \( c = \omega/k \) is determined by the expression

\[
c = \frac{(\alpha/k^2 + EI k^2)^{1/2}}{m_0^{1/2}} \tag{5}
\]

where the value \( c_{\text{min}} \) is often referred to as the track critical velocity. The above-mentioned typical track and ballast parameters and for an \( EI \) value of 4.85 MN/m², it follows from (5) that \( c_{\text{min}} = 326 \text{ m/s} \) (1174 km/h) which is much higher than the speeds of the fastest modern trains. However, for very soft soils, e.g. alluvial soils, characterized by very low stiffness \( \alpha \), values of \( c_{\text{min}} \) can be as low as 60–70 m/s and can be easily exceeded by even relatively moderate high-speed trains.

In practice, the value of \( c_{\text{min}} \) for a particular location can be estimated using equation (5), in which the stiffness of the equivalent Winkler foundation \( \alpha \) is expressed in terms of the real elastic moduli of the ground. There are different theoretical models that give such expressions (see, for example, reference [19]). Generally, it follows from these models that the track critical velocity is normally 10–30 per cent higher than the Rayleigh wave velocity for the same ground.

The solution of equation (1) with the right-hand side different from zero has different forms for small and large values of time \( t \). For the problem under consideration, of interest is the ‘established’ solution for large values of \( t \) which describes the track deflections as being at rest relative to the coordinate system moving at train speed \( \nu \), the so-called stationary solution. Obviously, this solution must depend only on the combination \( x - \nu t \). Using the notation \( p = \beta(x-\nu t) \), where \( \beta = (\alpha/(4EI))^{1/4} \), it is easy to obtain the stationary solution of equation (1) in the Fourier domain, \( W(p) \) (see, for example, reference [20]), where

\[
W(p) = \int_{-\infty}^{\infty} w(x)e^{-ipx}dx.
\]

Taking the inverse Fourier transform of \( W(p) \) allows derivation of the analytical expressions for \( w(x-\nu t) \), which have different forms depending on whether \( \nu < c_{\text{min}}, \nu = c_{\text{min}} \) or \( \nu > c_{\text{min}} \). The behaviour of \( w(x-\nu t) \) in all these cases is well known and will not be discussed here. It is worth mentioning, however, that if a train speed \( \nu \) approaches and exceeds the minimum phase velocity \( c_{\text{min}} \), the rail deflection amplitudes \( w \) experience a large resonance increase limited by track damping. Note that possible large rail deflections at train speeds approaching the track critical velocity may result even in train derailment, 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 (see, for example, references [9] and [17] to [19]).

2.3 Forces applied from sleepers to the ground

To calculate forces applied from sleepers to the ground, e.g. for a sleeper located at \( x = 0 \), use can be made of the following expression [12]:

\[
c_{\text{min}} = \left(\frac{4\alpha EI}{m_0^2}\right)^{1/4}
\]
\[ P(t) = T \left[ \frac{3.2 w(t)}{w_{\text{max}}(t)} \right] \left( \frac{d}{x_0} \right) \]  

(6)

where \( d \) is the sleeper periodicity and superscript ‘st’ corresponds to the quasi-static solution of equation (1), i.e. for \( m_0 \partial^2 w / \partial t^2 = 0 \). In particular, \( w_{\text{max}}^{\text{st}} \) is the maximum value of \( w(t) \) in quasi-static approximation, and \( x_0^{\text{st}} = \pi / \beta \) is the effective quasi-static track deflection distance.

As will be shown below, to describe generation of ground vibrations by moving trains, it is necessary to know the frequency spectrum of the force applied from each sleeper to the ground, \( P(\omega) \), rather than its time dependence, \( P(t) \). Note that, whereas a time domain solution \( P(t) \) has different forms for \( v < c_{\text{min}}, \, c_{\text{R}} < v < c_{\text{min}} \) and \( v > c_{\text{min}} \) respectively, its Fourier representation \( P(\omega) \) has the same form for all these cases. Bearing in mind that for \( x_0^{\text{st}} = \beta \omega \), it is possible to derive the following expression for \( P(\omega) \):

\[ P(\omega) = \frac{\left[ -12.8 T d \omega^2 \right]}{[\omega^4/\beta^4 \pi^4] - 4[\omega^4/(c_{\text{min}}^2 \beta^4)] - 8i([g \omega]/(\epsilon_{\text{min}} \beta)) + 4} \]  

(7)

where \( g = (m_0/\alpha)^{1/2} \omega_b \) is a non-dimensional damping parameter. Typical forms of the vertical force spectra \( P(\omega) \) calculated for a train travelling on very soft soil at speeds \( v = 20, \, 50 \) and \( 70 \) m/s (corresponding to the cases \( v < c_{\text{R}}, \, c_{\text{R}} < v < c_{\text{min}} \) and \( v > c_{\text{min}} \) respectively) are shown in Fig. 2. Calculations were performed for the following parameters of train, track and soil: \( T = 50 \) kN, \( d = 0.7 \) m, \( \beta = 1.28 \) m\(^{-1} \), \( c_{\text{R}} = 45 \) m/s, \( c_{\text{min}} = 65 \) m/s and \( g = 0.1 \). For relatively low train speeds, i.e. for \( v < c_{\text{R}} \), dynamic solution (7) for the force spectrum \( P(\omega) \) goes over to a quasi-static one [22]. As train speeds increase and approach or exceed the minimum track wave velocity, the spectra \( P(\omega) \) become broader and larger in amplitudes, and a second peak appears at higher frequencies.

The values of \( P(\omega) \) in the model under consideration are limited by track wave damping described by the non-dimensional damping parameter \( g \). The effect of track damping on the spectra \( P(\omega) \) is shown in Fig. 3 for \( v = 50 \) m/s (a) and \( 70 \) m/s (b), i.e. for the cases \( c_{\text{R}} < v < c_{\text{min}} \) and \( v > c_{\text{min}} \) respectively. As can be seen, the effect of damping is more pronounced in the latter case. For low train speeds, \( v < c_{\text{R}} \), the effect of track damping is negligibly small.
Fig. 3  Spectra of vertical forces applied from each sleeper to the ground (in N s) at train speeds $v = 50$ m/s (a) and 70 m/s (b) for three values of track damping: $g = 0.2$ (curves P1), 0.1 (curves P2) and 0.05 (curves P3); frequency $f$ is in Hz.
2.4 Calculation of generated ground vibrations

Calculation of ground vibrations generated by a moving train requires 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. The corresponding analytical formula, relating the frequency spectra of the vertical component of surface ground vibration velocity $v_z(0, y_0, \omega)$ at the point of observation $x = 0$ and $y = y_0$ with the sleeper force spectra $P(\omega)$ and geometrical parameters of the track and train, has the following form [7, 10–12]:

$$v_z(0, y_0, \omega) = P(\omega)D(\omega) \sum_{m=-\infty}^{\infty} \sum_{n=0}^{N-1} \left[ \frac{\exp(-\gamma m \rho m / c_R)}{\sqrt{P_m}} \right] \times \left[ 1 + \exp \left( \frac{i M \omega}{v} \right) \right] \exp \left[ i \frac{\omega}{v} (m d + n L) + i \frac{\omega}{c_R} \rho m \right]$$

where $D(\omega) = (1/2\pi)^{1/2}(-i\omega)q k_R^{1/2} k_t^{1/2} \exp(-i3\pi/4)/[\mu F'(k_R)]$ is a function describing properties of the Rayleigh surface waves generated by a single sleeper (for the problem under consideration, only the Rayleigh surface wave contribution need be considered, since Rayleigh waves transfer most of the vibration energy to remote locations). Here $k_R = \omega/c_R$ is the wave number of a Rayleigh wave propagating through the ground with the velocity $c_R$; terms $k_l = \omega/c_l$ and $k_t = \omega/c_t$ are the wave numbers of longitudinal and shear bulk elastic waves in the ground; $c_l$, $c_t$ and $\mu$ are the corresponding wave velocities and shear modulus; $\gamma = 0.001–0.1$ is an empirical constant describing the ‘strength’ of dissipation of Rayleigh waves in soil [23]. Term $q$ is defined as $q = [(k_R^2 - (k_l)^2)^{1/2}$, and the factor $F'(k_R)$ is the derivative $d/dk$ of the so-called Rayleigh determinant $F'(k) = (2k^2 - k_l^2)^2 - 4k^2(k^2 - k_t^2)^{1/2}((k^2 - k_l^2)^{1/2}$ taken at $k = k_R$; $\rho m = [y_0^2 + (md)^2]^{1/2}$ is the distance between a current radiating sleeper, characterized by the number $m$ and the point of observation $(x = 0, y = y_0)$; $N$ is the number of carriages, $M$ is the distance between the centres of bogies in each carriage and

Fig. 4 Spatial distributions of the surface vertical displacements (in arbitrary units) generated at the frequency component $f = 31.4$ Hz by a single axle load moving through a small part of a track consisting of 10 sleepers; the results are shown for (a) sub-Rayleigh speed and (b) trans-Rayleigh speed.
L is the total carriage length. Dimensionless quantity $A_n$ is an amplitude weight factor to account for different carriage masses (for simplicity, it is assumed that all carriage masses are equal, i.e. $A_n = 1$). Note that equation (8) is applicable for trains travelling at arbitrary speeds.

2.5 Special case of trans-Rayleigh trains

For ‘trans-Rayleigh trains’, i.e. trains travelling at speeds higher than the Rayleigh wave velocity in the ground, it follows from equation (8) that maximum radiation of ground vibrations (a ground vibration boom) takes place if the train speed $v$ and Rayleigh wave velocity $c_R$ satisfy the relation

$$\cos \Theta = \frac{1}{K} = \frac{c_R}{v}$$

(9)

where $\Theta$ is the observation angle. Since the observation angle $\Theta$ must be real ($\cos \Theta \leq 1$), the value of $K = v/c_R$ should be larger than 1; i.e. the train speed $v$ should be higher than the Rayleigh wave velocity $c_R$. Under this condition, a ground vibration boom takes place; i.e. ground vibrations are generated as quasi-plane Rayleigh surface waves symmetrically propagating at angles $\Theta$ with respect to the track, and with amplitudes much larger than those for ‘sub-Rayleigh trains’. The formation of a ground vibration boom is illustrated in Fig. 4, showing the spatial distributions of the ground surface vertical displacements generated at a chosen frequency component by a single axle load moving through a small part of a track consisting of 10 sleepers. The results are shown for sub-Rayleigh speed (a) and trans-Rayleigh speed (b). It can be seen that in the first case the generated ground vibrations propagate almost in all directions, whereas in the second case they are concentrated around angles $\Theta$ determined by equation (9).

3 GROUND VIBRATIONS FROM TGV OR EUROSTAR TRAINS

Ground vibration frequency spectra generated by complete TGV or Eurostar trains travelling on homogeneous ground at different speeds have been calculated using equations (7) and (8) for a limited number of sleepers ($m = 150$). It was assumed that a typical train consists of $N = 5$ equal carriages.
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, each carriage should be considered as having one-axle bogies separated by a distance $M = 15.9$ m. Other parameters were: $T = 100$ kN, $\gamma = 0.05$, $\beta = 1.28$ m$^{-1}$, $d = 0.7$ m, $c_R = 45$ m/s, $c_{\text{min}} = 65$ m/s, $g = 0.1$ and $y_0 = 30$ m, where $y_0$ is the distance from the track to the observation point.

The results of calculations of ground vibration spectra $v_z(f)$ (in dB, versus the reference level of $10^{-5}$ m/s) generated by the above-mentioned TGV or Eurostar trains are shown in Fig. 5 for three values of train speed: $v = 20$, 50 and 70 m/s (curves V1, V2 and V3 respectively). It can be seen that, for the trans-Rayleigh train speed of 50 m/s corresponding to the case $c_R < v < c_{\text{min}}$, the overall level of generated ground vibrations is much higher than for a sub-Rayleigh train speed of 20 m/s. For a train speed of 70 m/s, exceeding the value of the track critical velocity, $c_{\text{min}}$, a significant increase takes place at higher frequencies of generated ground vibration spectra. However, since the amplitudes of high-frequency components are generally low, the overall increase is not very large in comparison with that associated with ground vibration boom.

It is interesting to compare the above-described theory with the recent observations made on the railway line from Gothenburg to Malmö (see Section 1). Since no detailed experimental data are available at the moment, the same parameters of TGV trains (instead of Swedish X2000) have been used, and calculations of the vertical ground vibration velocity averaged over the frequency range 0–50 Hz have been carried out. Use was also made of the reported low value of Rayleigh wave velocity in the ground ($c_R = 45$ m/s), assuming that the Poisson ratio of the ground $\sigma$ was 0.25. To facilitate the comparison of the predicted increase in ground vibration level with the observed increase, the amplitudes of generated ground vibrations were calculated in linear units (m/s).

The resulting amplitudes as functions of train speed are shown in Fig. 6 for two values of track critical velocity: $c_{\text{min}} = 65$ m/s (curve V1) and $c_{\text{min}} = 10,000$ m/s (curve V2) (the latter very large value of $c_{\text{min}}$ describes the hypothetical case where track dynamic effects can be completely ignored). It can be seen that in both cases the predicted amplitudes of the vertical velocity component of
generated ground vibrations change from \( 2 \times 10^{-5} \text{ m/s} \) at \( v = 140 \text{ km/h} \) (38.8 m/s) to \( 16 \times 10^{-5} \text{ m/s} \) at \( v = 180 \text{ km/h} \) (50 m/s). Thus, the estimated eightfold increase in ground vibration level that follows from the above theory for the train speeds and Rayleigh wave velocity considered is in reasonable agreement with the tenfold increase recently observed experimentally for the Swedish high-speed railway line built on soft ground [8].

If train speed further increases and approaches or exceeds the track critical velocity (\( c_{\text{min}} = 65 \text{ m/s} \)), then the comparison of curves V1 and V2 shows that the level of generated ground vibrations also becomes larger (by a factor of approximately 1.5–2, as compared with the case of absence of track dynamic effects). This increase is not as large as in the case of ground vibration boom. However, since it occurs in combination with the latter, this gives a noticeable amplification of the resulting ground vibration impact.

4 CONCLUSIONS

The above-described theory of generating ground vibrations by high-speed trains shows that, if train speeds exceed the velocity of the Rayleigh surface waves in the supporting soil, a ground vibration boom occurs, resulting in a very large increase in amplitudes of generated vibrations. Crossing the track wave critical velocity results in further increase in generated ground vibrations, albeit not as dramatic as in the case of ground vibration boom.

Recent experimental observations of a ground vibration boom, made for Swedish X2000 trains travelling at speeds of 140–180 km/h, confirm the predictions of the theory. This implies that a railway-generated ground vibration boom is no longer an exotic theoretical effect with uncertain implications in the future. It is a reality for high-speed lines crossing soft soil, as are ‘supersonic’ or ‘trans-Rayleigh’ trains.

 Builders and operators of high-speed railways must be aware of the possible consequences of a ground vibration boom and large rail deflections. The direct relevance of these phenomena in the United Kingdom is in the construction of the Channel Tunnel Rail Link, especially on sites with soft alluvial soils, such as Rainham Marshes. Similar problems can also be expected to arise on other sites in Europe, especially in the Netherlands with its very soft soils.

It is too early at this stage to foresee how the phenomenon of railway-generated ground vibration boom and its amplification by track dynamics effects will be reflected in future standards on noise and vibration from high-speed trains. However, such an important parameter as the Rayleigh wave velocity in the ground for the sites considered can be expected to be present in all these standards indicating maximum train speeds beyond which excessive ground vibrations can be expected.

REFERENCES

11 Krylov, V. V. Spectra of low-frequency ground vibrations generated by high-speed trains on layered ground. J. Low Frequency Noise and Vibr., 1997, 16(4), 257–270.
12 Krylov, V. V. Effect of track properties on ground vibrations generated by high-speed trains. Acustica-acta Acustica, 1998, 84(1), 78–90.
17 Madshus, C. and Kaynia, A. M. High speed railway lines on soft ground: dynamic behaviour at critical train speed. In Proceedings of 6th International Workshop on Railway and


