

Modelling and measurements of critical train speed effects and associated track movements

A.J.F. Duley¹, L. Le Pen¹, D.J.Thompson¹, W. Powrie¹, G.V.R. Watson¹, P. Musgrave² and A. Cornish².

¹ *University of Southampton, Southampton, UK*

² *Network Rail, London, UK*

* Corresponding Author: A.Duley@soton.ac.uk

ABSTRACT As train speeds are increased, there is a greater likelihood of encountering critical velocity effects at sites with soft soil. These can lead to increased rates of track geometry degradation, poor ride quality and increased maintenance costs. These phenomena occur when the train speed approaches that of the Rayleigh waves of the underlying ground. A study of critical velocity effects is presented, based on a semi-analytical model of the vibration of the vehicle/track/ground system. Results from this model are compared with measured track deflections obtained at a site on a classic UK mainline at which large track displacements were observed following an increase in line speed from 160 km/h to 200 km/h. Geotechnical investigations have shown that the site is underlain by a layer of peat of low stiffness. By refining the parameters used in the model, assuming that the peat was the primary cause of the large track movements at high speed, it was possible to obtain reasonably close agreement between site measurements and the results from the model in terms of maximum deflections and frequency spectra of rail displacements. As the water table has been observed to be quite high at the site, an additional investigation is presented into the effect of the water level on the critical speed effects. Three levels of saturation are considered for the peat layer, ranging from fully saturated to relatively dry. The results suggest that a reduction in the water levels at the site is unlikely to lead to a reduction in the critical velocity effects.

1 INTRODUCTION

High-speed rail is becoming increasingly important in improving the capacity, attractiveness and carbon footprint of national infrastructure in many countries. Increases in the speeds of existing lines, as well as the construction of new routes, are desired. Higher speeds require straighter railway lines, which often mean crossing soft soils such as peats, organic clays and marine clays. Such ground types have traditionally been avoided due to having shear wave velocities as low as 30 ms^{-1} , contributing to low ground-borne surface (Rayleigh) wave speeds. As modern trains run at speeds of up to 300 km/h (83 ms^{-1}) they are increasingly likely to approach or exceed the Rayleigh wave speed of the underlying ground, potentially triggering large vertical track movements. This not only increases rates of track degradation and maintenance costs, but also affects ride quality. These so-called critical velocity effects have been observed in many countries worldwide. An improved understanding of the cause, and the ability to model potentially problematic locations would allow more cost-effective mitigation measures to be implemented.

Critical velocity effects were first reported by De Nie (1948) after making experimental observations of large deflections of railway lines on soft soil. Theoretical work in this area was then developed by authors such as Kenney (1954). Initial solutions for a moving load exciting a homogeneous elastic half-space, for speeds below, at and above the Rayleigh wave speed of the soil, were presented by Cole and Huth (1958) and Fryba (1972). Later authors such as Krylov (1998) and Sheng et al. (1999) incorporated layered ground geometry. This theoretical work has since been substantiated by various case studies, for example by Karlström and Boström (2006), Kaynia et al. (2000) and Krylov et al., (2000). Recently 2.5D models, based on a wavenumber transform in the longitudinal direction, have been used in an attempt to reach a balance between model efficiency and flexibility (e.g. Sheng et al., 2006). There are still, however, very few sites for which data and observations are available in the literature to allow model validation.

Real ground often shows soil layering and inhomogeneity. The influence of ground stratification on traffic-induced vibrations has been investigated by, for example Lombaert et al., (2001), who used a numerical model to replicate a variety of situations and concluded that soil stratification has a considerable influence on both the frequency content and peak particle velocity of free field vibrations.

The properties of underlying soil layers were found to be most important at low frequencies, with the top layers dominating at high frequencies.

Groundwater levels effectively introduce additional ground layering. Schevenels et al.,(2004) used a numerical model of a single layer over a halfspace to show that ground water levels affect vibrations in three key ways – reducing soil compressibility, and causing potential resonance of the dry layer and potential interference between refraction of P-waves in the dry layer and the surface waves.

This paper presents an investigation using an established model (TGV - Sheng et al., 2004) to calculate velocity-dependent displacements, up to and beyond the critical velocity, using a relatively simple ground geometry model and estimates of soil parameters. This was carried out in conjunction with measurements at a site in the UK. An investigation is also presented into the influence of groundwater level on critical velocity effects. The model set-up and the site measurements are described, and example results are given and discussed.

2 CASE STUDY BACKGROUND

2.1 Site Information

The study site was found to experience large track displacements following an increase in line speed from 160 km/h to 200 km/h. The track is located in a cutting and is poorly drained. Geotechnical investigations showed the site to be underlain by a horizon of peat, over layers of stiffer sand, clay and gravel. The peat layer was found to be between 1.4 and 4 m thick. The low stiffness of the peat is believed to have been the main cause of the large track movements when the train speed was increased. Borehole data were only available along the line of the track; no information was available in the direction perpendicular to the track. No geophysical parameters are available from these borehole investigations. A range of trains run on this line, with the fastest (Class 390) being selected for this case study.

2.2 Geophone Monitoring

Vertical track movements at the site were monitored using geophones, small seismic devices which output a voltage proportional to velocity. Geophones were attached to nine alternating sleepers, allowing movements over a 10 m length of the track to be recorded. The signal is filtered and integrated to obtain the displacement. The monitoring and analysis methods used are described in Bowness et al. (2006).

Vertical deflection measurements were taken during the passage of 11 trains, of varying type and consisting of between 3 and 11 cars. Figure 1 shows typical processed geophone data in the form of vertical displacement against time. Owing to the high-pass filtering applied before integration, the trace apparently contains both upward and downward displacements (relative to datum) whereas in reality the displacement of the sleepers from data is consistently downwards. The parameter of interest, which is obtained correctly from the analysis, is the peak-to-trough displacement amplitude during each axle passage, which in this example is more than 6 mm.

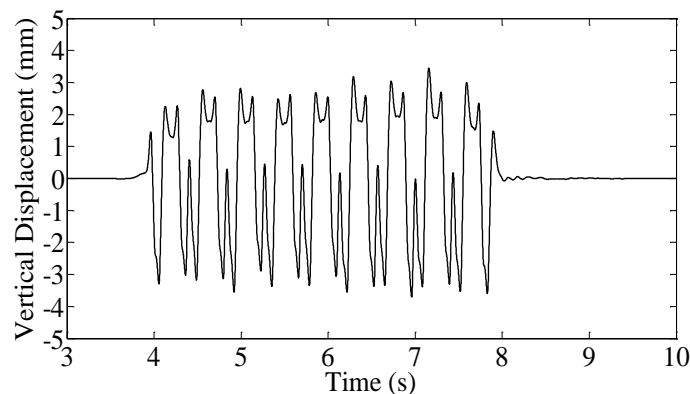


Figure 1: Geophone trace showing vertical displacement of a sleeper during the passage of a 9-car Class 390 at 195 km/h (54 m/s).

3 BASIS OF THE MODEL

Analyses were carried out using TGV, a semi-analytical model for ground vibration in the wavenumber domain developed at the University of Southampton (Sheng et al., 2004). The ground is modelled as a layered half-space using flexibility matrices, in terms of wavenumbers k_x and k_y in the x and y directions. The model calculates the response due to the moving axle loads and vertical rail irregularities.

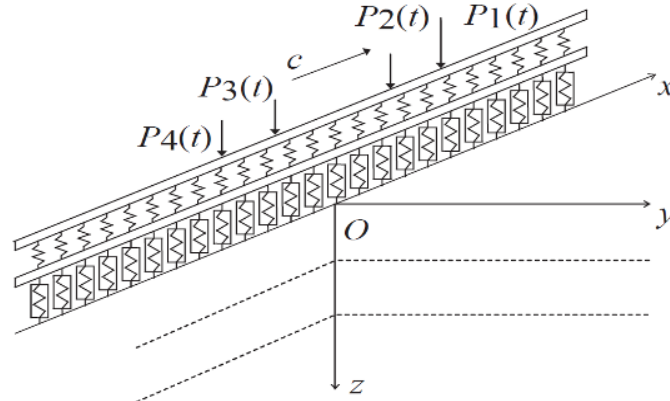


Figure 2: Schematic of TGV model for track-ground system (Sheng et al., 2003)

Vehicles are represented as multiple rigid body systems and only the vertical dynamics is considered. The track is modelled as a beam supported by vertical springs and layers of mass (Figure 2), where $P_1(t), \dots, P_n(t)$ represent the vertical wheel-rail forces for n wheelsets. It is assumed that each wheelset is always in contact with the rails.

4 MODEL SET-UP

4.1 Ground Geometry and Loading Types

The ground is modelled as a layer of peat of specified thickness above a stiffer halfspace, representing the comparatively stiffer layers of sand, gravel and clay beneath the peat. The following loading configurations were used:

1. Moving axle loads of a single vehicle (allowing interaction of the displacements from the two wheelsets in a bogie),
2. Four full vehicles (representing a train, including dynamic excitation due to track unevenness).

For case 2, as well as the moving load, excitation frequencies from 0.25 to 120 Hz with 80 logarithmically spaced steps were used. By limiting the overall model size and mesh density it was possible to run all models on a desktop computer. A length and width of 268 m was sufficient to accommodate a 4 car train (length 116 m) and the decaying waves.

4.2 Initial Ground Parameters

Limited measurements of the ground wavespeeds made beside the track at the study site provided an initial estimate of the dilational (P) and shear (S) wave speeds for the lower layers of sand and gravel, indicating a P wave speed of 768 ms^{-1} and an S wave speed in the range $95\text{--}200 \text{ ms}^{-1}$. An S wave speed of 95 ms^{-1} was selected to represent the ground beneath the peat in the model.

It was not possible to estimate the wavespeed of the peat from the site measurements, so the S wave speed was initially set to 53 ms^{-1} (the train speed causing the largest measured movements on the site). The Poisson's ratio was set to 0.11 (Rowe et al., 1984) and the density to 1050 kg/m^3 , allowing the P wave speed and Young's modulus to be derived. The derived Young's modulus of 6.3 MPa is reasonable for slightly clayey peat, with all other ground parameters assigned typical values for that ground type (Table 1). The thickness of the peat layer was set at 2 m, representative of the range found from the borehole measurements.

Table 1: Initial Ground Parameters

Ground type	Density	Damping loss factor – constant (Twice the damping ratio)	S wave speed	P wave speed
Peat	1050 kgm ⁻³	0.3	53 ms ⁻¹	79 ms ⁻¹
Stiffer halfspace	2000 kgm ⁻³	0.1	95 ms ⁻¹	768 ms ⁻¹

4.3 Track and Train Parameters

Parameter values typical of UK track were used representing UIC60 rail and mono-block concrete sleepers. Where possible, train parameters specific to Class 390's were adopted; otherwise values typical of higher speed passenger trains were used.

Table 2: Track (for a single track, i.e. two rails) and Vehicle (Class 390) Parameters.

Track parameter	Value	Track parameter	Value	Vehicle parameter	Value	Vehicle parameter	Value
Rail mass	120 kgm ⁻¹	Rail pad damping loss factor	0.2	Axle spacing	2.7 m	Wheelset mass	1750 kg
Sleeper mass	461.5 kgm ⁻¹	Rail damping loss factor	0.01	Bogie spacing	17 m	Bogie pitching moment of inertia	3000 kg.m ²
Ballast mass	1740 kgm ⁻¹	Ballast damping loss factor	0.04	Bogie to end of vehicle	2.906 m	Primary suspension stiffness	258 x10 ³ Nm ⁻¹
Rail bending stiffness	1.29x10 ⁷ Nm ⁻²	Track width	2.5 m	Car body mass	475 x10 ² kg	Primary suspension viscous damping	4250 Ns/m
Ballast stiffness	4.64x10 ⁹ Nm ⁻²	Ballast width	3.1 m	Car body pitching moment of inertia	206 x10 ⁴ kg.m ²	Secondary suspension stiffness	410 x10 ³ Nm ⁻¹
Rail pad stiffness	3.69x10 ⁸ Nm ⁻²	Track roughness	FRA Class 3	Bogie mass	2325 kg	Secondary suspension viscous damping	200x10 ² Nsm ⁻¹

5 RESULTS AND DISCUSSION

5.1 Initial and Refined Parameters

Using the initial parameters given in Section 4, the model was run with both loading types. Figure 3 shows the maximum peak-to-trough displacements calculated using load case 1, plotted as a function of train speed. Measured results are also included for comparison, with error bars indicating the range of deflections on the various sleepers that were monitored. The displacements are consistently around 30% greater than those measured on site, while the critical velocity appears to be over-estimated. Consequently, the initial parameter estimates need to be adjusted to give a better match the site results. The excessive displacements obtained from the model may be partly attributable to the lack of lateral confinement of the peat layer in the model as each layer is considered to be of infinite horizontal extent. The inability to represent the varying thickness of the peat horizon along the track evident in the borehole records may also have had an impact on the results. Nevertheless, revised parameters have been sought using the same basic model.

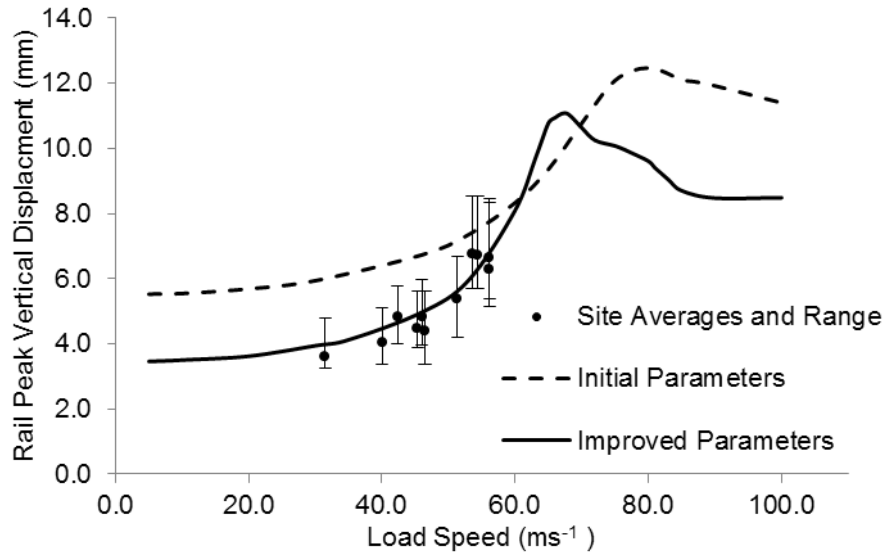


Figure 3: Displacements vs. load speed for a single vehicle running across a 2 m peat layer above a stiffer halfspace, using initial and refined parameters. Geophone measurements are also shown.

The model was re-run with a large number of parameter combinations in an attempt to match more closely the site measurements, with the objective of reducing both the low speed deflections and the critical velocity. The impact of changing a parameter value varied by parameter type - increasing the Young's modulus reduced the displacements but also increased the critical speed, whereas increasing the density maintained the general shape of the displacement curve whilst reducing the critical velocity and slightly decreasing the displacements, owing to its impact on wave speeds. Increasing the damping of the peat reduced the slope of the curve and hence the peak displacements, but it also increased the critical velocity. An increase in the Poisson's ratio reduced displacements, especially at lower speeds.

The S-wave speed of the stiffer half-space was increased to 130 ms^{-1} which is still within the range measured on site and corresponds to a Young's modulus of 100 MPa, a reasonable value for a combination of sands and gravels. Table 3 shows the parameter combination giving the best fit; the results are also presented in Figure 3.

Table 3: Refined Ground Parameters

Ground type	Density	Damping loss factor – constant	S wave speed	P wave speed	Young's modulus
Peat	1600 kgm^{-3}	0.2	35 ms^{-1}	1400 ms^{-1}	5.88 MPa
Stiffer halfspace	2000 kgm^{-3}	0.1	130 ms^{-1}	768 ms^{-1}	100.01 MPa

A close match to the site measurements was achieved. The parameters required to produce these results are generally reasonable except for the density and Young's modulus of the peat, which are unusually high. However, this could be interpreted as aggregating and averaging out the properties needed to reproduce the measured behaviour for a lens of peat confined by stiffer, denser materials. The calculated critical velocity of 67 ms^{-1} is greater than the speed of the fastest trains on the site and so cannot be validated. The variation in the measured deflections of the fastest trains is thought to have been due to variations in load rather than an indication that critical velocity has been reached.

5.2 Assessing Impact of Saturation Levels

It has been observed that the ground water level at the case study site is extremely high, sitting just above the base of the ballast layer. The high value of Poisson's ratio used in the refined parameters, and the correspondingly high P wave speed are consistent with saturated soil. The properties of peat

are highly dependent on its water content; therefore three sets of parameters were chosen to represent three possible levels of saturation:

- 1) Completely saturated peat ,
- 2) Relatively dry peat, uniformly saturated with a saturation level of 45%,
- 3) A 1 m thick layer of completely saturated peat overlain by a 1 m thick layer of relatively dry peat.

The porosity of the peat was assumed to be 90%, with a dry density of 400 kgm^{-3} (Walczak et al., 2002). This allows calculation of densities for full saturation (equal to $400 \text{ kgm}^{-3} + [0.9 \cdot 1000 \text{ kgm}^{-3}]$) and partial saturation of 45% (equal to $400 \text{ kgm}^{-3} + [0.4 \cdot 1000 \text{ kgm}^{-3}]$). As the water content of soil increases, the compressional wave speed for low amplitude vibration increases to a value a little larger than that of water whereas the shear wave speed is unaffected (Schevenels et al., 2004). The earlier shear modulus was therefore kept constant for all three scenarios, at the value used in the earlier refined peat parameter set (1.96 MPa). The Poisson's ratio was adjusted to give P wave speeds as shown in Table 4. The stiffer halfspace was unchanged from the previous refined parameter value set.

Table 4: Peat parameters for various levels of saturation

Peat type	Density	Damping loss factor – constant	S wave speed	P wave speed	Young's modulus	Poisson's ratio
Saturated	1300 kgm^{-3}	0.2	39 ms^{-1}	1586 ms^{-1}	5.88 MPa	0.4997
Relatively dry	800 kgm^{-3}	0.2	49 ms^{-1}	93 ms^{-1}	5.10 MPa	0.3

The deflections for the three scenarios are shown in Figure 4. Clear differences can be seen in the shape and amplitude of the calculated displacement curves. As the degree of saturation increases, the displacements decrease, owing to the reduction in compressibility caused by the presence of water in the pore spaces. These results imply that reducing the saturation level of the peat will tend to increase track displacements.

The critical velocities for the relatively dry and layered soils are very similar, at 79 ms^{-1} and 80 ms^{-1} respectively, with these two cases also producing displacement curves of similar gradient and shape. In contrast the critical velocity for the saturated case is lower at 73 ms^{-1} .

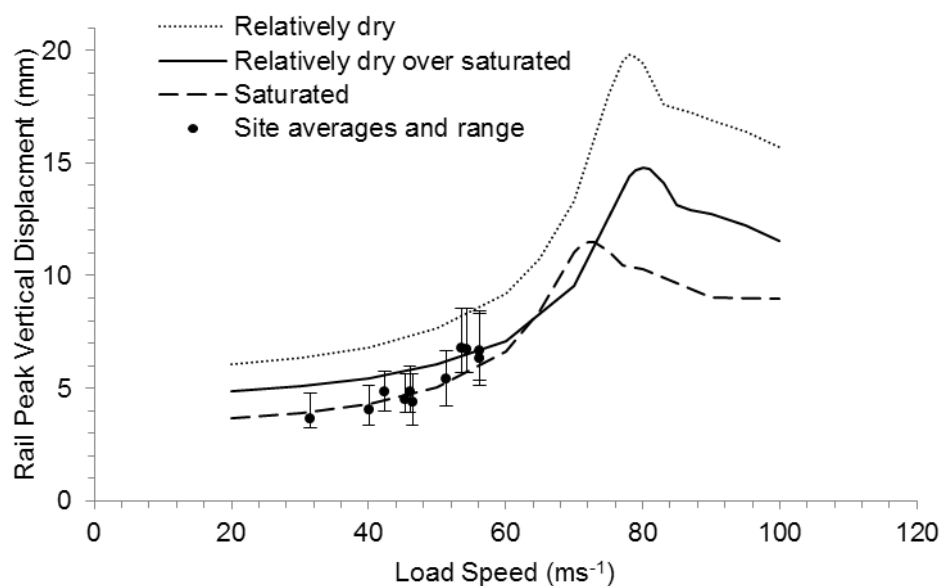


Figure 4: Displacements vs. load speed for a single vehicle running across a 2 m peat layer above a stiffer halfspace, using parameters given in Table 4. Geophone measurements are also shown.

5.3 Analysis including dynamic excitation

Figure 5 shows the frequency spectrum of the vibration velocity obtained from the full vibration analysis including the dynamic excitation. These results are for a train speed of 53 ms^{-1} , corresponding to the fastest trains at the site. Results are shown for the three different levels of saturation considered above. The spectrum of measured vibration is also shown. The response to quasi-static excitation is dominant at low frequencies and the dynamic component at high frequencies. As the train speed increases so does the frequency of the transition between these two components. At 53 ms^{-1} it is found to be at approximately 30 Hz for the fully saturated soil and 25 Hz for the other two cases. For frequencies above 10 Hz the quasi-static vertical velocity is independent of the soil properties. However, much larger differences are found in the dynamic results, leading to the large differences in the total velocities above 50 Hz.

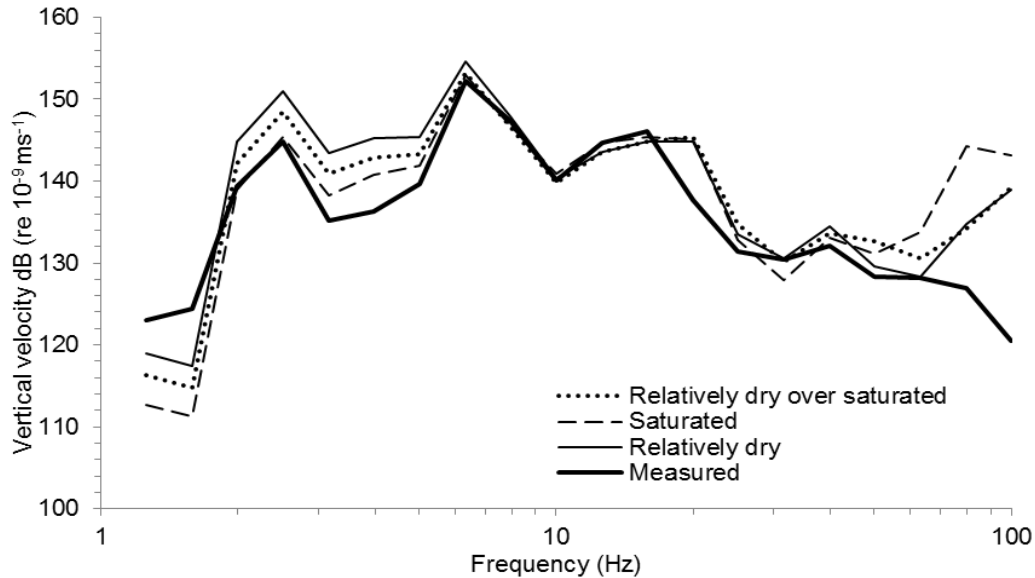


Figure 5: Full train pass-by vibration response for 4 vehicles running at 53 ms^{-1} across a 2 m layer of peat over a stiffer halfspace using parameters given in Table 4. Geophone measurements are also shown.

The track receptances (i.e. the displacement due to a unit force as a function of frequency) are shown in Figure 6 for each soil condition. These results are for a moving load of 53 ms^{-1} . The vehicle wheelset receptance, based on its unsprung mass, is also shown for comparison.

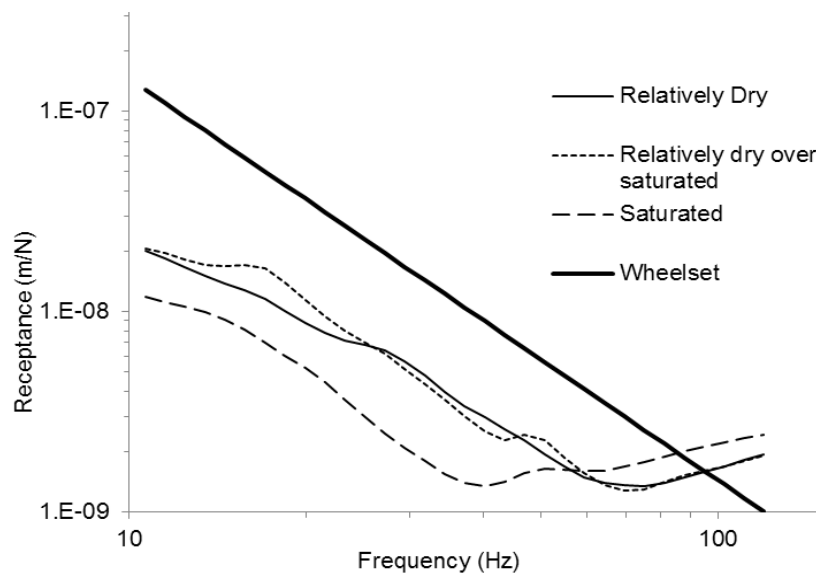


Figure 6: Track receptances for different soil conditions, and wheelset receptance.

A peak in the vertical velocity level is expected at the frequency at which the rail and wheelset receptances cross, known as the vehicle-track coupled resonance (Thompson, 2008). At low frequencies the receptance of the track on the fully saturated soil is less than the others, but above 60 Hz it is higher than that of the other soil cases. Consequently, the coupled vehicle-track resonance is expected to occur at a lower frequency in this case, leading to the higher vibration levels observed in the model for the saturated soil in Figure 5.

6 CONCLUSIONS

A study has been presented of the modelling of critical speed effects based on a site in the UK. A semi-analytical model (TGV) has been used with a ground geometry based on a layer of peat overlying a stiffer halfspace. Initial calculated displacements, obtained using best estimates of ground properties from the site, were much larger than those measured. Through refinement of the soil parameters a much closer agreement between the modelled and measured results was achieved in terms of maximum deflections and frequency spectra of the rail vibration.

An initial investigation was also presented, carried out using the same model into the possible impacts of the currently high water level at the site. The results suggest that reducing the groundwater level at the site is likely to lead to an increase in critical velocity effects.

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