Assessing the risk of critical velocity effects at railway sites using site investigation and advanced laboratory testing

A. Duley[1#] [0000-0001-7170-1347], B.N. Madhusudhan[2][0000-0002-2570-5934], L. Le Pen[2][0000-0002-4362-3895], D. Thompson[3] [0000-0002-7964-5906] and W.Powrie[2][0000-0002-2271-0826]

[1] Jacobs UK Ltd., Aperture@ Pynes Hill Court, Exeter, UK
[2] University of Southampton, Infrastructure Research Group, Boldrewood Innovation Campus, Southampton, Hampshire, SO16 7QF, UK
[3] University of Southampton, Institute of Sound and Vibration, Highfield campus, Southampton, Hampshire, SO17 1BJ, UK.
[#]alice.duley@jacobs.com

Abstract. As train speeds increase on existing rail networks, and new high speed routes are constructed, the likelihood of a line experiencing large track displacements associated with what are commonly termed critical velocity effects increases. The phenomenon occurs as the train speed approaches the speed of surface (Rayleigh) waves in the underlying ground. At a certain proportion of this speed the track deflections begin to increase above those for static loading, slowly at first and then more rapidly, reaching a maximum at a “critical” velocity. Larger trackbed deflections may cause increased rates of track deterioration, maintenance needs and in the worst cases risks to safety. Therefore, it is important to be able to predict which sites are susceptible to critical velocity effects and to determine threshold speeds below which they are not influential. Where these thresholds are exceeded, mitigation measures can be considered. Reliable prediction of critical velocity effects using numerical modelling and other analytical tools require selection of a representative ground model and parameters. This paper describes a programme of site measurements, sampling and advanced laboratory testing to create a ground model for a site on the UK railway network known to experience critical velocity effects.

Keywords: Critical velocity, resonant column, organic silt, Rayleigh wave, railway, railroad, high speed trains, bender element, ground model.

1 Introduction

In many countries there is pressure to increase train speeds on existing rail networks, as well as for higher speed new routes. As train speeds are increased, tracks that have previously performed acceptably may start to deteriorate and in extreme cases experience large movements during the passage of an individual train, as a result of what are commonly termed critical velocity effects. The phenomenon occurs when the train speed approaches the speed of surface (Rayleigh) waves in the underlying ground – defining the critical velocity of a site. These effects are also of potential concern for new high-speed lines where straighter routes may cross areas of soft ground, which have traditionally been avoided owing to their inherently low wave speeds. It is important to be able to predict where critical velocity effects may occur, and where necessary take steps to mitigate them. For economic reasons, it is equally important to avoid such mitigation where it is not necessary.

Critical velocity effects have been observed in many countries. The most well documented and highly cited occurrence is that at Ledsgård in Sweden, where soft organic clays caused the onset of critical velocity effects at approximately 150 km/h. Track displacements of up to 15 mm were recorded at a train speed of 200 km/h [1]. A strong trend is found across multiple sites when track displacements are normalized relative to low speed (quasi-static) values, and train speeds relative to the estimated site critical velocity (Figure 1). For reasons of safety and the avoidance of excessive maintenance, it is often recommended that line speeds be limited to a factor of the site critical velocity (X_{VC}). Values of 0.6 to 0.7 are commonly suggested, as this is the normalized speed at which displacement magnitudes begin to significantly increase [2,3,4].

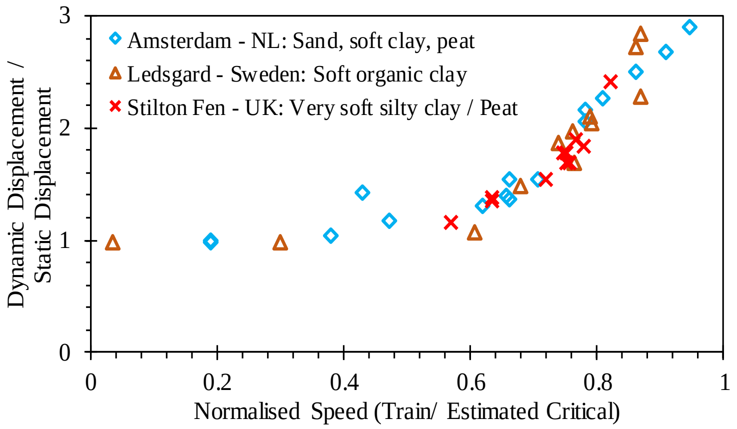

Fig. 1. Normalised displacement-speed curve for a range of critical velocity sites, after [3].

There is still some uncertainty over the suitable value of X_{VC}. Some locations run well at higher factors; for example in Ireland, trains run satisfactorily at critical velocity factors X_{VC} greater than 0.7 [5]. While the appropriate value for X_{VC} may be debated, and factors such as the absolute magnitude of displacements must also be considered, estimation of the actual critical velocity at a site is important. For example, for X_{VC} = 0.6, under- or over- estimating the critical velocity by 15% would result in a range of speed limits equivalent to applying X_{VC} = 0.5 or 0.7. This paper summarises, with reference to a case study, a process to produce a ground model from which the critical velocity may be estimated.

1.1 Causes and Modelling of Critical Velocity Effects

The shear wave velocity of a soil, being related to the Rayleigh wave velocity, is a useful indicator of the likelihood of critical velocity effects. Softer, less dense ground is most likely to be susceptible both because displacements per unit load are greater and the Rayleigh wave speed (and hence the train critical velocity) is lower. Models of railway vibration are often based on the assumption that the ground can be modelled as a layered elastic half space, with each soil layer behaving in a linear elastic isotropic manner. However, beyond a threshold strain, the shear modulus of a soil degrades with increasing strain, resulting in non-linearity. Damping is also non-linear once the linear strain threshold has been exceeded.

Strains during train passage at Ledsgård were high enough to take the soils beyond any limit of linearity. Maximum cyclic strains at the site were reported as 1% in the embankment and 0.8% in the underlying natural organic clay. The secant shear modulus reduced to 10-50 % of the small strain value while the damping ratio increased by 20-100 % [1]. Inclusion of these degraded state parameters in an analytical model has a significant impact on the calculated ground displacements and critical velocity at a site, and a model based on non-degraded parameters underestimates track displacements [e.g. 1,7,8,9]

Critical velocity effects have been analysed using models of varying degrees of complexity, ranging from linear-elastic 2D [e.g. 10], through 2.5D and 3D equivalent-linear models [e.g. 7, 11], to 3D models with a fully non-linear soil response [e.g. 8, 9]. Whether the aim is to more effectively identify potential problem areas or to produce a full non-linear displacement response estimate, results are only as accurate as the ground model adopted. Soil layering, density, shear modulus and variation in damping with strain are essential for an effective model. Critical velocity effects are most likely on soft soils, for which there is a relative paucity of published shear modulus degradation data.

2 Assessing Ground Quality

Typically, the ground up to a depth of 15 m - 20 m below track level may be excited by train passage. However, owing to the elliptical nature of the ground movement associated with Rayleigh waves and the attenuation of energy in the upper ground layers, the overall critical velocity is influenced more by the layers of ground closest to the track than those at the full depth of excitation. The stiffness properties of the track itself also plays a part.

Ground wave speeds can be directly measured by in-situ and laboratory testing, and inferred via empirical and other correlations with related parameters. The Rayleigh wave speed in a soil is usually approximately 90 to 95% of the shear wave speed [12]. In-situ testing techniques include MASW (Multi-channel Analysis of Surface Waves), SCPT (Seismic Cone Penetration Test) and other seismic-impulse based techniques. Laboratory techniques include resonant column (RC), bender element (BE) and triaxial tests, all of which require undisturbed samples to be retrieved from the site of interest.

Other key modelling parameters such as ground layering, densities and damping can be obtained through a combination of in-situ and laboratory methods.

Laboratory testing is necessary to measure the non-linear relationship between shear wave speed / damping and strain. The degradation of the shear modulus with strain can be measured in triaxial and resonant column tests. Only the resonant column apparatus is able to measure also the strain-dependency of soil damping.

The resonant column apparatus has a torsional drivehead to which a cylindrical sample is attached. The base of the is sample fixed. The drivehead is rotated clockwise and anticlockwise through small angles at a range of frequencies, with the response of an accelerometer on the drivehead monitored. The frequency at which the greatest response is measured is the resonant frequency of the specimen. From this, the shear wave speed can be calculated. Damping is measured by monitoring the accelerometer after the sample has been excited at its resonant frequency and then cut off to vibrate freely.

Bender elements are very small piezo-electric transducers, which operate as a pair at either end of a sample. A voltage is applied to one end to excite a wave and the arrival time at the other end is recorded, from which the shear wave speed is calculated.

Fig. 2. RC example sample, and RC equipment before pressure cell put in position.

3 Case Study Site

3.1 Background

Following an increase in line speed from 160 km/h to 200 km/h, a site on the UK classic network was found to experience large track displacements along a run of sleepers. To quantify the increased track deflection, site measurements of sleeper velocity during train passage were carried out using geophones. Geophone data from a sequence of sleepers showed that the track was deflecting in excess of 6 mm (Figure 3). This is large compared with the typically <2 mm movement on well performing routes. It may result in increased rates of track deterioration, which local track maintenance records confirm. Historical geotechnical investigations showed the site to be underlain by a layer of soft organic material, sitting over layers of stiffer sands and gravel. The soft layer varies between 2 m and 4 m in thickness and is present along a 50 m length of track. The site sits within a slight basin and cutting, with several streams and brooks in the area. These factors explain why the site has a high water table.

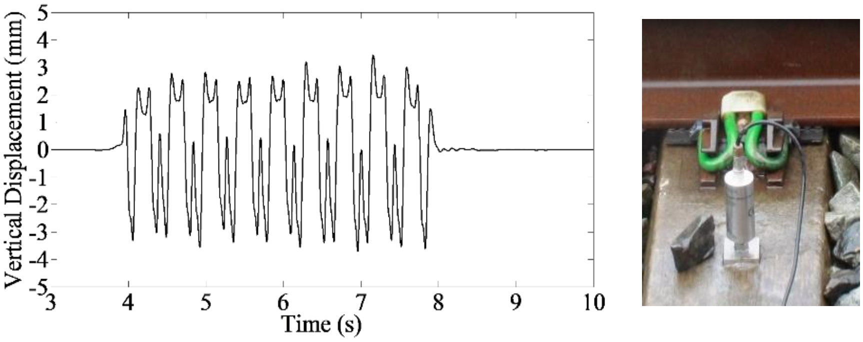

Fig. 3. Typical geophone trace showing track displacement, and geophone fitted on sleeper. Note that the ‘zero’ point for the geophone does not represent the ‘zero’ point for the track [13].

3.2 In-Situ Ground Investigation

During a night-time possession of the line, a tracked windowless sampling rig was used to drill two boreholes directly through the centre line of the track. The bores were positioned within sleeper bays at chainages targeting the maximum thickness of the soft layer shown on the historical geotechnical investigation (GHS1), and slightly beyond the previously-indicated extent (GHS2). Each bore penetrated 6 m below sleeper level (bSL), with samples below the trial pit retained inside the casings in 1m lengths and the bores logged at 1m intervals. Super Heavy Dynamic Probes (SHDP) were carried out at both locations from the base of the bore to 10 m bSL.

Sample tubes were transported to the laboratory for full logging and index testing. 15 whole samples suitable for advanced laboratory testing, of at least 150 mm in length, were successfully retrieved from the bores. Of key interest in the results is a layer of soft to very soft organic silt, which extends beneath the ballast to approximately 3 m to 4 m bSL. Soils of this nature tend to have a low shear wave velocity. Examples of the silt materials are shown in Figure 4. The two bores are summarised in Figure 5. The ballast layer is thicker than typical (up to 0.9 m) - a possible indication of increased ballast maintenance activity at the site. Below the soft silt are layers of clay, sand and gravel, which are unlikely to be the cause of the critical velocity effects.

Fig. 4. Typical organic silt samples.

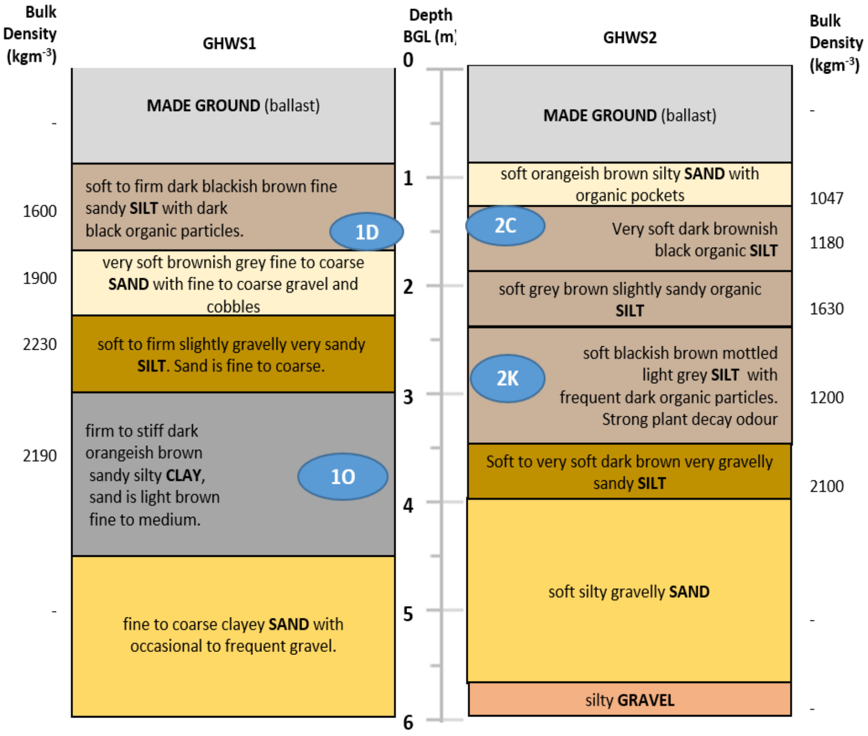

Fig. 5. Borehole summary with selected sample locations.

Index Testing

Figure 6 shows the variation in density with depth, based on 50 mm dia. density ring tests completed in the laboratory. There is some variation in density between the two boreholes, with GHS1 consistently denser. Determination of density from density rings is subject to some error in very variable soils such as these. Nonetheless, a large variation with depth was found. The densities in GHS2 were especially low, with values generally between 1100 kgm^{-3} and 1400 kgm^{-3} for the first 3.5 m below ground level. A typical clay soil might be expected to have a density of approximately 2000 kgm^{-3}, almost twice the lowest value measured in GHS2. Low density soils tend to have low stiffness, hence likely to be the cause of critical velocity problems at the site.

The variation in moisture content with depth is also shown in Figure 6. As with density, a significant difference is apparent between the boreholes. The denser GHS1 has generally far lower moisture contents than GHS2, and the values are also more consistent. Greater variability is found for GHS2, with unusually high moisture content being an indicator of the organic material in the soil.

Other index testing was also completed on selected samples. Atterberg tests showed the organic sandy silts to be non-plastic, while the firm sandy clay has low plasticity. Ignition tests were carried out on 8 organic silt samples to measure total and volatile solids, resulting in 6 high-organic and 2 medium-organic ratings.

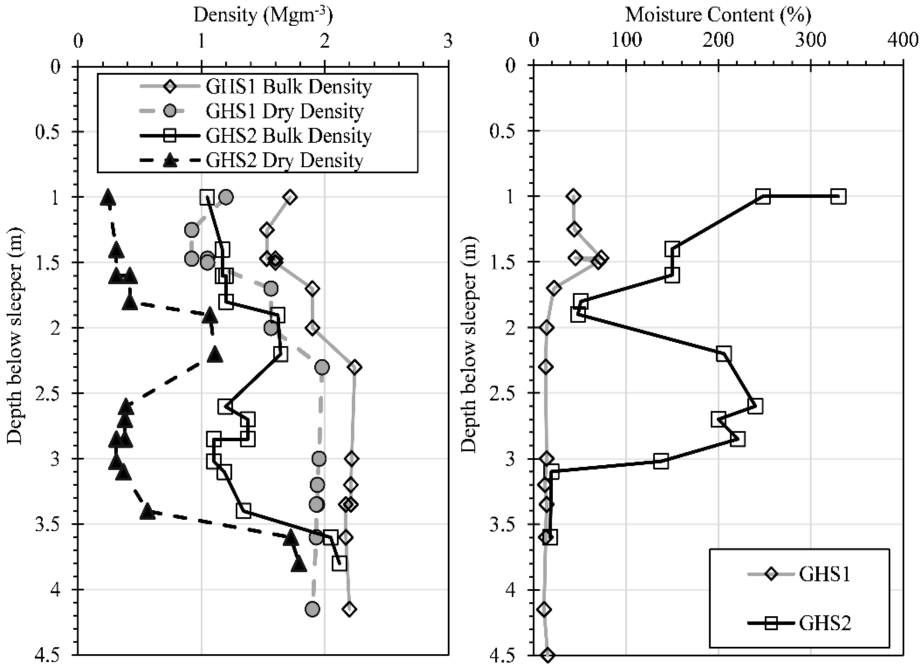

Fig. 6. Density and moisture content variation with depth, both site bores.

Super Heavy Dynamic Probe (SHDP) Results

The SHDP results gave good indications of layer density boundaries, which correlate well to borehole results. Consistent with the density evaluation for the top 6 m of ground in the borehole logs (Figure 6a), the SHDP results indicate that the ground below this depth is stiffer at borehole GHS1. The average blowcount was approximately 60% greater for GHS1 at depths >7.5 m bSL than for GHS2. At the maximum penetration depth of 10 m bSL, the two SHDP blowcounts show a degree of convergence.

Derivation of further parameters from the SHDP relies on converting the blowcounts to SPT equivalents and applying empirical correlations. Common correlations for relative density for non-cohesive materials were applied [14,15], as the ground is believed to consist of sands and gravels. GHS1 equates to medium-dense and dense material, while GHS2 is loose to 7 m bSL, underlain by medium-dense material.

4 Laboratory Testing

4.1 Resonant Column and Bender Elements

Test Procedure

A standard resonant column apparatus was adapted following the improvement methods of [16] and [17], (Figure 2). The end caps were modified to contain vertical bender elements, which provide fast, non-destructive direct measurements of shear and compressional wave speeds at very small strains. As the soft soils tested were likely to have resonant frequencies below those typically measured in the RC, calibration focused on the low stiffness / frequency range using brass, nylon and aluminium calibration bars.

Four site samples were selected to represent the most geotechnically interesting materials, and carefully trimmed from the sampling diameter of 100 mm down to the resonant column specimen size of 70 mm. The material type and location of each sample are shown in Figure 5. Several testing pressures were calculated for each, based on the depth of sample retrieval, the range of likely water tables and possible future surcharges. The test process for each sample was as follows: 1) saturation; 2) consolidation to the lowest test pressure; 3) bender element measurements; 4) resonant frequency measurements at increasing strains, ensuring strains remained recoverable; 5) repeat bender element and very small strain resonant column measurements to ensure no permanent deformation occurred; 6) steps 2 to 6 repeated for remaining test pressures.

Results: Shear Modulus and Shear Wave Speed

Non-destructive torsional tests were successfully completed on the four soft organic silt samples, at a range of test pressures and strains. The very soft samples necessitated repositioning of the resonant column drivehead during testing due to the large amount of consolidation. Bender element measurements were also successfully taken. The resonant column measured shear moduli, normalized by the small strain shear modulus G_O, show varying rates of degradation with strain (Figure 7). The stiffest sample (GH1O-clay) shows greater rates of degradation, and at lower strains, than the silt samples. For example, averaged across the testing pressures, at distortional strain levels of 0.01% the shear moduli of the samples showed reductions to GH2K – 98%, GH2C – 93%, GH1D – 87%, GH1O – 77%.

Very low shear moduli (and therefore shear wavespeeds) were measured for all the organic silt samples, with G_O >10 MPa for most pressures (Figure 8).The silt samples also showed a very low rate of strength gain with pressure increase in comparison with the clay. The low rate of increase in modulus with pressure of the soft organic silt samples means that soils normally considered to be at a sufficient depth to have a reasonable shear modulus may have a very low value. Threshold strain limits, where the shear modulus begins to degrade, vary by sample and by pressure, but are higher for the organic silts than the clay, consistent with the impact of organic content reported by [18].

Excellent agreement was also found between bender element and resonant column measurements of shear modulus / shear wave speed (Figure 8). The softest samples have shear wave speeds as low as 70 m/s (250 km/h). In comparison, modern high-speed railways are often designed for 400 km/h running. Poisson’s ratio was derived from the bender element compressional and shear wave measurements.

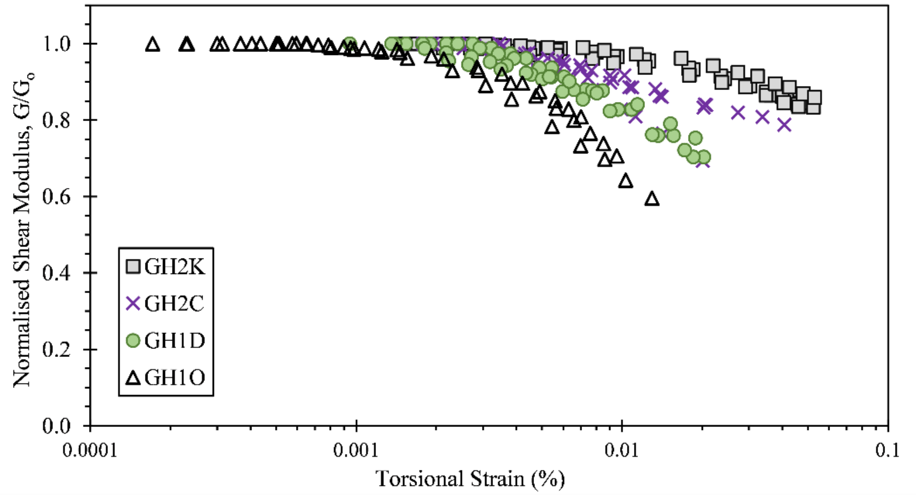

Fig. 7. Normalised resonant column shear modulus degradation with strain for all samples

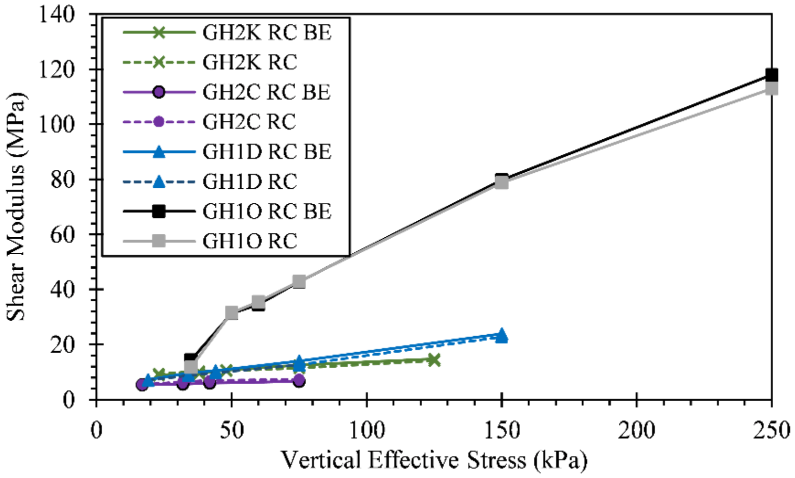

Fig. 8. Small strain shear modulus variation with pressure; resonant column and bender element.

Results: Damping

The increase in damping ratio with strain was also measured for all samples. Damping is higher for the clay and sandy silt samples than for the soft / very soft organic silts. No significant variation in damping with the applied test pressures was found. The measured values sit within expected ranges for typical clay and organic soil types. A typical result is presented in Figure 9 for GH2C, a very soft high-organic silt.

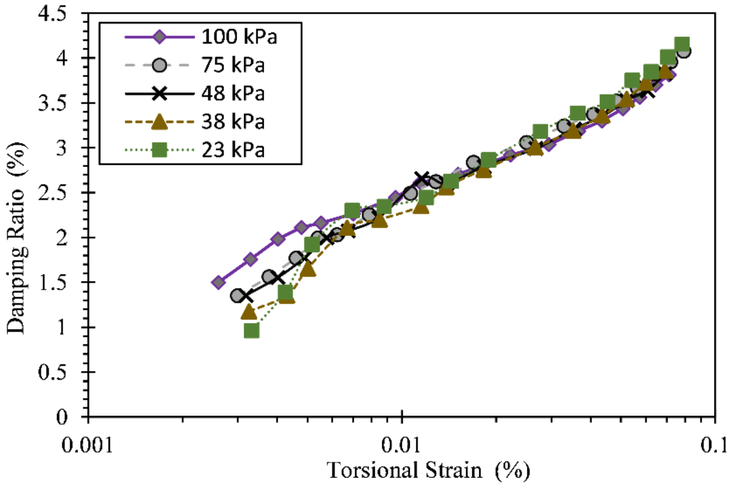

Fig. 9. Example damping variation with strain in resonant column tests: Sample GH2K.

5 Integration Of Laboratory And In-situ Parameters

To build a ground model, it is necessary to consider data obtained from all sources. The first restriction is that most models include only horizontal layering. For this reason an average thickness for the important soft silt layer must be selected, which is believed to be a basin of varying thickness with a maximum of 4 m. A value of 2.5 m was chosen, with the thickness and material type of the layers above and below the silt selected from a combination of the historical site boreholes, the new site boreholes and the SHDP. The site is believed to be saturated below the ballast. The final ground model and small-strain parameters are presented in Table 1. Accurate modelling will require degraded values of soil parameters to be considered.

Table 1. Gravel Hole ground model: Small-strain parameters

Material	Thickness (m)	Bulk Density (kgm^{-3})	Shear Modulus Go (MPa)	Shear Wave Speed Vs (ms^{-1})	Small Strain Damping Ratio (%)	Poisson's Ratio
BALLAST Type	0.7	1600	57	189	2.0	0.3
Very soft to soft highly organic SILT	2.5	1200	6.8	75	2.1	0.482
Firm sandy silty CLAY	0.7	2100	20	97	3.7	0.497
Clayey SAND and GRAVEL	To Depth	2000	52	161	3.0	0.45

Properties were assigned to each material based on laboratory tests on relevant samples. Results for laboratory tests were also compared with other published results for similar soil types where possible, to give added confidence. Typical published values were selected for materials where no laboratory testing took place.

6 Conclusion and Recommendations

An extensive site investigation was carried out, including the drilling of new boreholes and the completion of dynamic probe tests. After full index testing of 20 metres of borehole samples, a large data set of soil stratigraphy, density and other general index measurements has been produced. Testing of samples in advanced laboratory equipment has been completed, providing data for stiffness and damping variation with strain from the resonant column, with confirmatory shear modulus testing completed with bender elements. The highly organic silt is a material for which little data are published, and so provide a useful dataset for future work. In combination with pre-existing seismic measurements and track displacement measurements, the data provide all the information required for the use of this site as a new critical velocity case study.

Recommendations for assessing ground models for critical velocity sites are as follows.

- In-situ seismic testing is less useful on sites where the underlying ground layers are uneven and the position of the railway is such that suitable test locations are unavailable or inaccessible. Sole reliance on such tests is not recommended, as soils at soft sites may have unusually low densities, which are unlikely to be assumed in the seismic dispersion curve analysis.
- Super Heavy Dynamic probe test data are useful in building an expanded picture of the site stratigraphy rather than relying on boreholes alone, at lower expense and with reduced invasiveness.
- The addition of bender elements to a resonant column test is a very effective method for providing confirmatory measurements of shear wave speed / shear modulus for minimal additional cost and time.
- The resonant column is the only method capable of providing both shear modulus and damping degradation measurements relatively quickly and easily – both key modelling parameters.
- If it is thought that a site may suffer critical velocity effects and advanced laboratory testing is not possible, it is essential to carefully consider the ground material before selecting typical shear moduli and strain degradation / damping variation rates. Organic content and / or the presence soft materials such as silts will greatly affect the selected values.

Acknowledgments. The work described in this paper was funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and HS2 Ltd as part of the Track Systems for High Speed Railways: Getting It Right project (EP/K03765X. The site access was also facilitated by Network Rail and AECOM who assisted with historical records and the site investigation.

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