

Scoping prediction of re-radiated ground-borne noise and vibration near high speed rail lines with variable soils



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ABSTRACT

This paper outlines a vibration prediction tool, ScopeRail, capable of predicting in-door noise and vibration, within structures in close proximity to high speed railway lines. The tool is designed to rapidly predict vibration levels over large track distances, while using historical soil information to increase accuracy. Model results are compared to an alternative, commonly used, scoping model and it is found that ScopeRail offers higher accuracy predictions. This increased accuracy can potentially reduce the cost of vibration environmental impact assessments for new high speed rail lines.

To develop the tool, a three-dimensional finite element model is first outlined capable of simulating vibration generation and propagation from high speed rail lines. A vast array of model permutations are computed to assess the effect of each input parameter on absolute ground vibration levels. These relations are analysed using a machine learning approach, resulting in a model that can instantly predict ground vibration levels in the presence of different train speeds and soil profiles. Then a collection of empirical factors are coupled with the model to allow for the prediction of structural vibration and in-door noise in buildings located near high speed lines. Additional factors are also used to enable the prediction of vibrations in the presence of abatement measures (e.g. ballast mats and floating slab tracks) and additional excitation mechanisms (e.g. wheel flats and switches/crossings).

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1. Introduction

The rapid deployment of high speed rail (HSR) infrastructure has led to an increased number of properties and structures being located in close proximity to high speed rail lines [7,12]. In comparison to traditional inter-city rail, HSR speeds can potentially generate elevated levels of vibration both within the track structure and in the free field. In the free field these vibrations can impact negatively on the local environment, causing properties to shake and walls/floors to generate indoor noise [15]. This can result in personal distress to those inhabiting such properties, and in the loss of building functionality (e.g. for buildings sensitive to vibration such as hospitals, manufacturing industries and places of worship [78]).

Therefore in many countries, before a new line is constructed, it is compulsory to undertake a vibration assessment exercise to identify the stakeholders that may experience negative side-effects. To determine these stakeholders as early as possible, the vibration levels from a new line must be calculated at the design stage. With the aim of predicting vibration levels, much research has been undertaken into the analysis of moving loads on a half-space [1,26,47]. Alternatively, [53] proposed a frequency domain model that accounted for the contribution of each sleeper on the vibration field, and used Greens functions to model ground wave propagation effects.

Alternative frequency domain approaches have since been proposed by [72,73,79], which used a combination of transfer functions for the train, track and soil to calculate vibration levels, and at large distances from the track. Auersch [3] also used transfer functions to model the effect of moving loads and vibration through a layered soil.

Other frequency domain approaches were presented by [36,35] who used the pipe-in-pipe (PiP) method to predict vibration levels for underground railway lines [8,74,27]. Several authors have also

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presented a three dimensional (3D) approach to modelling train passage using a combination of the finite element (FE) and boundary element (BE) method. The suitability of both the 3D FE-BE formulations and PiP approaches were compared and found to perform well [29].

Several time domain formulations have also been proposed for simulating railway vibration. Although work has been undertaken to adapt the finite difference time domain (FDTD) method for moving load problems [76,45], the majority of research has been performed using the FE method (and the coupled FE-BE method [62]). Recently [80] presented a 2D FE analysis to determine the effect of train speed on track characteristics. An alternative, advanced 3D model was presented by [51] who used a sub-structuring approach to model the propagation of vibration through the track, track and soil. Similarly, [22] used a fully 3D FE approach to model vibrations from moving trains and analysed the effect of critical velocities. Lastly, Ref. [11] used a fully 3D FE approach to facilitate the modelling of the complex track geometry and its contribution to railway vibration levels.

A challenge with both numerical frequency domain and numerical time domain models is that their computational run times are prohibitive for initial scoping assessment. If large sections of railway track require analysis then it is vital that predictions can be made with low computational effort.

In an attempt to achieve this, [69] proposed a straightforward mathematical tool to rapidly predict soil absolute vibration velocity levels in decibels and root mean squared values. The model only considered the contribution of Rayleigh waves in its solution and the track was considered as a continuous structure. Results were compared to field results obtained in [31] and it was found that the modelling accuracy was comparable to more computationally demanding numerical approaches.

An alternative model also based on the data collected in [31] was developed by [24] to predict absolute vibrations from high speed rail lines. This empirical approach used curve fitting techniques to develop relationships between train speed and distance from the track, with geological conditions largely ignored. This curve was then adjusted based on empirically derived factors to account for changes in soil-building coupling and track configuration.

This paper presents an empirically based model (ScopeRail) that builds upon [14] to facilitate the prediction of vibration decibels, in the presence of variable track-forms and in multiple building types. Furthermore, new SPT relationships are defined to convert historical soil data into model input data. The model uses a machine learning approach to approximate relationships for the effect of soil layering on vibration transmission. These relationships are then combined with empirical factors to facilitate rapid vibration prediction for a wide array of track and building characteristics. ScopeRail is then compared to the performance of the original [24] approach and it is found to offer enhanced performance.

2. Modelling philosophy

Railway vibration scoping models are used to assess vibration levels quickly and efficiently during the planning stage of a new line. Their goal is to predict vibration levels across large sections of track (in a conservative manner) to identify key areas that are likely to be effected by elevated vibration levels. Then these areas can then be investigated further using more in-depth analysis. To predict vibration levels over wide areas it is vital that scoping models can be deployed with minimal computational requirements. With this in mind, accuracy is sometimes sacrificed in preference for reduced computational requirements. This means

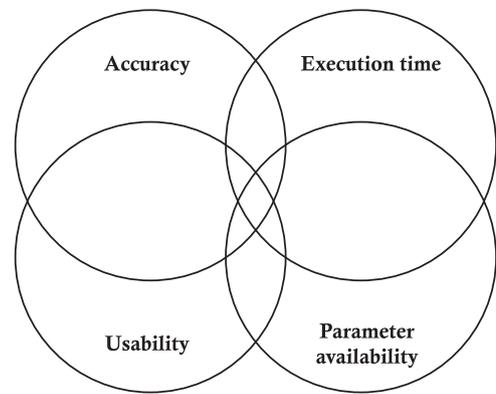


Fig. 1. Vibration prediction models—development considerations.

that vibration levels can be often overestimated and that detailed analysis is performed in areas where it was not required. Detailed railway vibration analyses are cost intensive and therefore this results in unnecessary additional project costs.

In addition to computational requirements and prediction accuracy, both parameter availability and usability are important considerations when deploying a scoping vibration prediction model. Usability is important from a practical point of view because a model that has a long learning curve or requires extensive prior engineering knowledge. Similarly, the model output must be compatible with the existing vibration standards governing the project. Similarly, parameter availability is important because if highly detailed soil information is needed for large areas then field experiments may be required which is undesirable. Instead, for scoping assessment, it is more advantageous to utilise rudimentary soil information in the form of historical records, where possible, to quickly determine a simplified soil profile. For high speed lines, the process of gathering historical soil data is performed at an early stage (for track dynamics purposes) and therefore can also be utilised within a ground vibration prediction model. These four equally desirable scoping model characteristics are outlined in Fig. 1.

3. Modelling approach

The modelling approach used to develop ScopeRail was composed of two distinct parts. Firstly a FE model was developed that was capable of predicting high speed railway ground-borne vibration time histories. This model was then computed many times to build up a database of velocity time histories for different soil conditions, train speeds and distances from the track. The second step involved a statistical analysis of results using a machine learning approach to achieve a model that could quickly and accurately predict vibration levels in the presence of varying soil conditions.

3.1. FE model development

The finite element model consisted of three distinct, fully coupled components to describe the train, track and soil respectively. All components had one axis of symmetry and therefore only half of each required modelling. The soil was modelled using linear elastic, eight noded, three dimensional brick elements with dimensions 0.3 m in each direction. Four of the six soil boundaries were truncated using infinite elements, described using an exponential decay function to simulate an infinitely long domain. The top boundary was the location of the free surface and the horizontal displacement was constrained in the direction

perpendicular to the track thus accounting for the soil symmetry. Rather than utilise a spherical geometry [11,51] to improve infinite element performance, a uniformly meshed rectangular model was preferred.

The track model was fully three-dimensional (Fig. 2) thus allowing for the simulation of the complex geometries associated with its structure. This overcame some of the assumptions associated with the simplified track modelling approaches as presented by [51,22]. The transmission of forces between each track component was simulated in a realistic manner. The track conformed to the layout commonly found on high speed rail lines in mainland Europe and was constructed from subgrade, subballast and ballast layers, supporting evenly spaced sleepers at 0.6 m spacings. The rail was connected to the sleepers and modelled using 0.1 m long beam elements. The track material properties are show in Table 1.

The vehicle was modelled using a lumped mass, multi-body dynamics approach. Three masses were used to simulate the car, bogie and wheel respectively, and were connected using spring/damper elements. Although the soil and track equations of motion were developed directly using the commercial FE software ABAQUS, the equations of motion for the vehicle were written manually and then coupled with the ABAQUS solver. This allowed for an efficient method to compute the force input to the track and for the wheel to be coupled with the rail using a non-linear Hertzian spring as described in [43,10]. The vehicle model and coupling mechanism is shown in Fig. 3. The vehicle was assumed to be a Thalys high speed train with properties as defined in [50].

3.2. ScopeRail model development

Although the FE model could model railway tracks in detail and was able to predict vibration time histories, its run times were too long for it to be used for railway vibration scoping assessments. Therefore it was used as the basis to develop another model, with

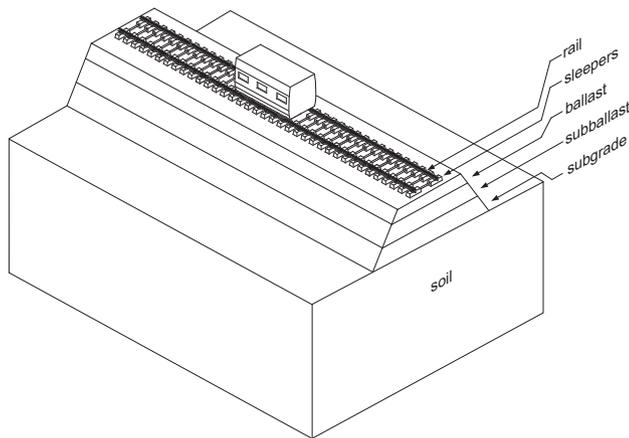


Fig. 2. FE model schematic.

Table 1 Track material properties.

	Young's modulus (MPa)	Poisson's ratio	Density (kg/m ³)	Layer thickness (m)
Rail	210,000	0.28	7900	
Sleepers	20,000	0.25	2400	
Ballast	200	0.3	1600	0.3
Subballast	130	0.3	2000	0.2
Subgrade	90	0.3	2000	0.5

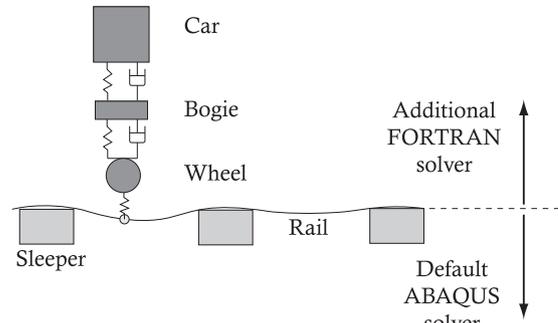


Fig. 3. Vehicle model and coupling mechanism.

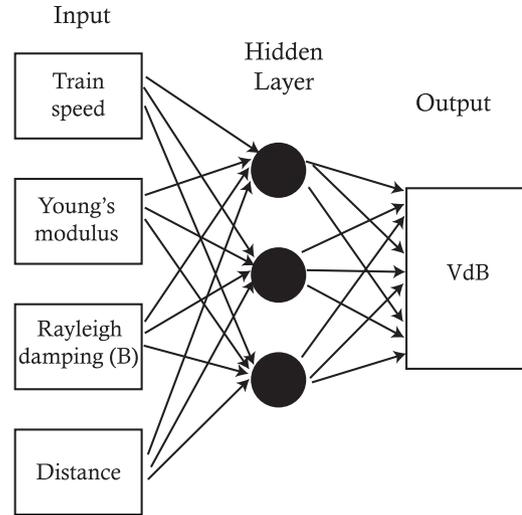


Fig. 4. One layer neural network schematic.

much lower computational demands, known as ScopeRail. To do so, a machine learning approach was used in an attempt to map train, track and soil characteristics to resultant absolute ground vibration levels.

First, a sensitivity analysis was undertaken to determine the most influential parameters that contributed to the generation of ground borne vibration from rail lines. The least influential parameters and those with large standard deviations (e.g. wheel/rail defects) were excluded from model development. A more detailed explanation of these tests can be found in [14,16].

One of the most important parameters affecting ground vibration propagation is soil characteristics [3]. To include soil properties within the scoping model, two alternative approaches were undertaken. The first approach was to consider the soil as a homogenous half space (i.e. a single layer) and the second was to consider the soil as a two layer medium. It should be noted that although an infinite number of soil configurations exist in practice, for the purpose of a scoping model, a limited number of input parameters was desirable. This was because it is difficult to obtain detailed soil information for large geographical areas. Therefore, extending the model to three or more layers was considered undesirable. The key input/output model parameters for the one layer and two layer cases are shown in Figs. 4 and 5 respectively.

3.3. Vibration metrics

The complexity of seismic wave propagation prohibited the prediction of raw time history signals using machine learning. Instead, key vibration indicators were calculated using raw

ABAQUS model vibration time histories and then used as the outputs/targets for neural network construction.

Many national and international metrics have been proposed for railway vibration assessment (Table 2). A challenge with their use is that each standard uses different criteria to assess vibration levels making it difficult to compare standards and to classify vibration levels universally. For example, the UK and Spain use acceleration to quantify vibration whereas Germany and America use velocity criteria. Similar differences exist between frequency weighting curves, time averaging procedures, units of measurement and metrics. Comprehensive reviews of existing standards can be found in [28,23].

Although the scoping model outlined in [14] was capable of predicting KB_{max} [20] and PPV values, these were less compatible with empirical vibration relationships used to convert ground vibration into indoor noise. Therefore, with the ultimate aim of maximising compatibility and usability, ScopeRail was redeveloped to predict vibration decibels (VdB_{max} —hereafter denoted simply VdB) as outlined in [24]. VdB was a logarithmic based vibration scale, with the maximum value offering a useful individual absolute measurement of vibration. It was calculated using Eq. (1), where v_{rms} was the moving average of the raw velocity time history, calculated over a one second time period ('slow'

setting). v_0 was the reference level of background vibration, for which a constant value of 2.54×10^{-6} m/s was chosen.

$$VdB = 20 \log_{10} \frac{v_{\text{rms}}}{v_0} \quad (1)$$

4. Using historical soil data within a scoping model

The advantage of ScopeRail over some alternative vibration scoping models was that it was capable of accounting for soil conditions within its prediction. At the vibration scoping stage of a high speed rail project rudimentary soil data is often available as a by-product from track design/selection process. Therefore this information can be reused within a scoping model. Despite this, if a comprehensive record of soil data is not available then it may be necessary to construct soil profiles manually from historical information. These historical records usually relate to tests such as borehole logs and SPT, which are not directly compatible with the properties required to model wave propagation. Therefore, it is difficult to utilise historical data within previously developed models such as [14].

To overcome this, a variety of previously proposed empirical relationships were investigated for the purpose of mapping the most common types of exiting historical test records to wave propagation parameters. These relationships were used to develop a range of new equations, which were then incorporated within ScopeRail.

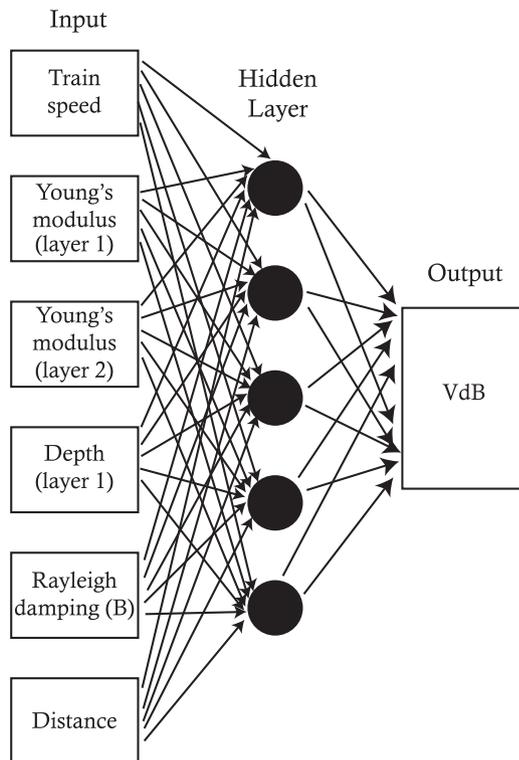


Fig. 5. Two layer neural network schematic.

4.1. Utilising historical SPT data

An advantage of using Standard Penetration Test (SPT) N -values to determine FE modelling properties is that historically the SPT test has been the most widely performed test and national resources such as [6] provide an extensive database of borehole logs. Therefore it is often possible to obtain SPT data without the financial outlay required to perform physical tests.

Additionally, a wide body of research exists for correlating SPT N -values with physical soil properties. Therefore, it is possible to use SPT data to obtain soil properties that are more reliable than using soil only description data. Despite this, a challenge with the SPT test is that the methodology is not performed consistently and parameters such as the drop height can vary between countries. Robertson et al. [67] presented correction factors to account for these inconsistencies although some authors have questioned whether these factors lead to more reliable results. Additionally, it should be noted that all SPT N -value correlations are based on soils experiencing low strain levels (i.e. the assumption of small strain theory).

Fig. 6 presents correlations between SPT N -values and shear wave speeds for general soils. The overall deviation between correlations is low, apart from [70,41], which both seem to over-estimate shear wave velocity.

Rather than use SPT correlations to classify all generic soil types, empirical relationships have also been presented for individual soil types. Each of these is based upon whether the soil is

Table 2
National and international vibration standards. (Recreated from [23]).

Country	Relevant standard(s)	Country	Relevant standard(s)
Austria	ONORM 9012:2010	Spain	Real Decreto 1307/2007
Germany	DIN 4150-2:1999	Sweden	SS 460 48 61:1992
Italy	UNI 9614:1990	UK	BS 6472-1:2008, BS 7385-2:1993
Netherlands	SBR Richtlijn—Deel B (2002)	USA	FRA (2012), FTA (2006)
Norway	NS 8176:2005	International	ISO 2631-1:1997, ISO 2631-2:2003

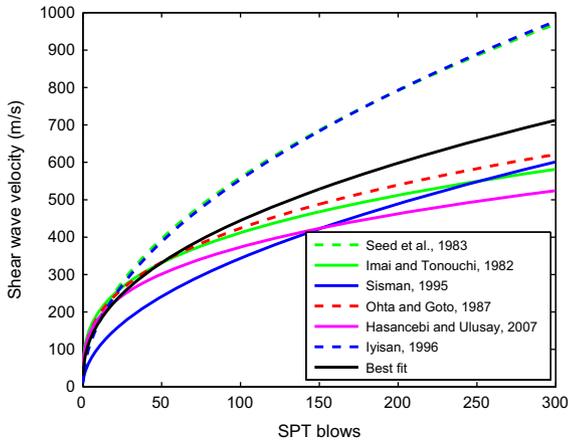


Fig. 6. SPT shear wave velocity correlations—all soils. [70,39,75,64,32,41].

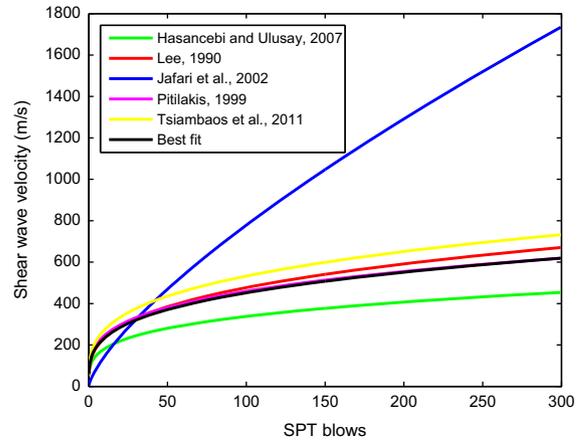


Fig. 9. SPT correlations—Clay. [32,56,42,66,77].

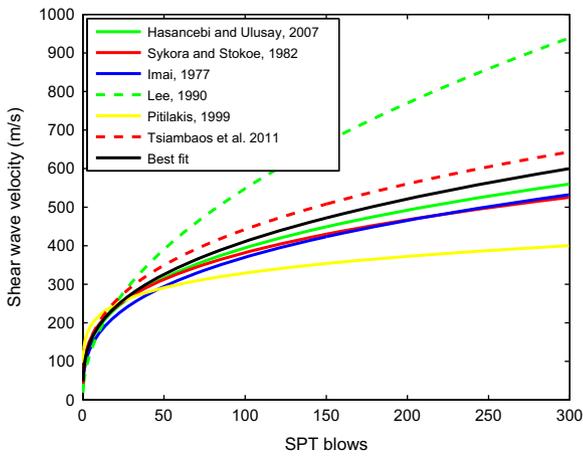


Fig. 7. SPT correlations—Sand. [32,38,56,66,77].

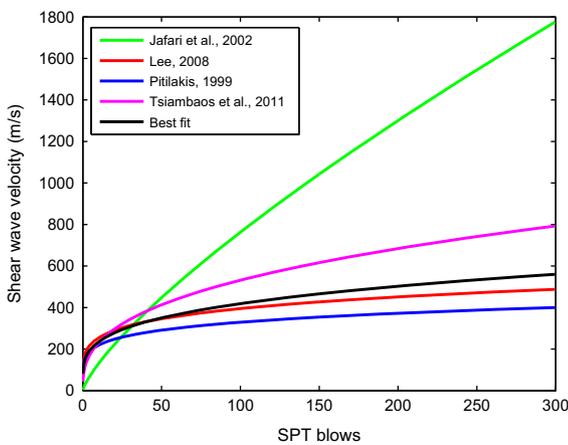


Fig. 8. SPT correlations—Silt. [42,55,66,77].

Table 3
Best fit SPT 'N-value' correlations.

Soil type	SPT relationship	Standard deviation (m/s)
General soils	$V_s = 62.9 \times N^{0.425}$	111.7
Sands	$V_s = 86.71 \times N^{0.3386}$	81.6
Clays	$V_s = 120.8 \times N^{0.2865}$	64.5
Silts	$V_s = 127.1 \times N^{0.2595}$	102.9

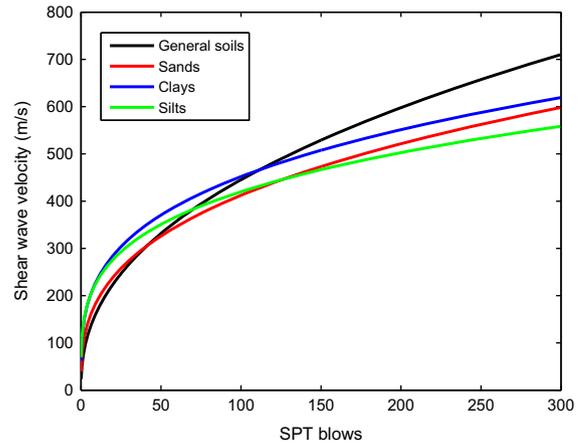


Fig. 10. Best fit SPT 'N-value' correlations.

a sand, clay or silt; information which is typically recorded when performing SPT testing.

Figs. 7–9 show relationships for sand, silt and clay respectively. For each soil type, relationships are relatively well correlated with each alternative relationship. Exceptions are the relationships proposed by [42], which for each soil, overestimates the shear wave velocity.

In addition to the relationships shown in Figs. 6–9, authors such as [71] have proposed correlations based on a greater number of variables (e.g. soil depth) in attempt to improve accuracy.

Rather than attempt to utilise a variety of SPT relationships, one new relationship for each soil type was developed. These new relationships were best fit correlations between all other relationships and are shown using a black line in Figs. 6–9. For both the silt and clay relationships, the equations presented by [42] were ignored because they exhibited a poor correlation with all other proposed relationships. The new relationships are described numerically in Table 3 and plotted in Fig. 10. As expected, the SPT relationships proposed for generic soil shear wave speeds had the largest standard deviation. Silts had a relatively large standard deviation and clays had the lowest at 64.5 m/s.

4.2. Utilising historical CPT data

The Cone penetration test (CPT) test is an alternative and more sophisticated penetration experiment in which a metal cone is pushed into soil and the penetrative resistance (q_c) is measured. The cone typically has a diameter of 35.7 mm², cast at a 60° angle and is pushed, with the aid of a land vehicle, into the soil at a constant rate.

In addition to cone tip resistance, sleeve friction (f_s) is commonly measured. Less commonly, piezocone penetration tests are used to measure pore water pressure and sometimes seismic cone penetration tests are used to measure shear wave velocity.

Although CPT testing is becoming more widespread, SPT testing remains more common place and historical data relating to SPT N -values is more freely available. One explanation for this is that due to the force required to push the cone into soils, the CPT method can only be used for relatively soft soils. Therefore, researchers such as [9] have attempted to correlate CPT results with SPT N -values. This approach is not recommended for the purpose of using empirical correlations to estimate FE parameters because it creates an additional layer of uncertainty. Instead, several authors have presented formulations based directly on CPT results, a variety of which are shown in Table 4.

For these relationships, σ is effective stress, k_2 is a coefficient function of relative density, ' q_t ' is the corrected cone tip resistance [19] and e_0 is the void ratio. The relationships have not been plotted graphically because of their dependence on a variety of soil parameters. This makes it challenging to make direct comparisons.

4.3. Utilising historical laboratory data

Lab testing involves extracting soil samples from the test site, transporting them to the lab and performing controlled

experiments to determine characteristics that are difficult to obtain using in-situ tests.

A variety of lab testing methodologies are available including bender element testing, resonant column testing, ultrasonic pulse testing and more traditionally, tri-axial testing.

A major advantage of lab testing is that the samples are tested under controlled conditions and therefore allow for a more accurate determination of soil properties. Despite this, due to inevitable sample disturbances caused during soil sample extraction and transportation, the properties of a soil at the time of lab testing are not always similar to the properties of the soil in-situ.

Classical lab testing refers to tests such as the quick undrained triaxial test to determine undrained shear strength [21]. They also include other tests to determine properties such as bulk density, moisture content, liquid limit and plastic limit. Although these soil properties (except density) are not required for FE simulation, correlations have been proposed to map them more closely to parameters such as Young's modulus [34].

For vibration prediction purposes, it is sometimes the case that classical lab testing data is available in addition to existing borehole data. Therefore empirical correlations between lab data and FE parameters may be useful for validating SPT correlations. Despite this, if a new soil lab investigation is being performed then bender element and resonant column testing techniques are preferable to classical lab testing. This is because the aforementioned tests can determine FE parameters directly, rather than approximating them using empirical relationships.

One of the most common empirical relationships between lab test results and shear modulus is:

$$\mu = AF(e_0)(\sigma'_0)^n \tag{2}$$

$F(e_0)$ is a function of the void ratio, σ'_0 is the effective confining stress and n is non-dimensional. A range of suggested values based

Table 4
CPT empirical relationships.

Soil property	Equation	Soil type	Refs.
Shear modulus	$1000 \times k_2 \times \sigma^{0.5}$	Sand	[65]
Shear wave velocity	$50 \times ((q_c/p_a)^{0.43} - 3)$	Sand	[65]
Shear wave velocity	$277 \times q_t^{0.13} \times \sigma^{0.27}$	Sand	[4]
Shear wave velocity	$(10.1 \times \log(q_t) - 11.4)^{1.67} \times (f_s/q_t \times 100)^{0.3}$	General soils	[33]
Shear wave velocity	$118.8 \times \log(f_s) + 18.5$	General soils	[59]
Shear wave velocity	$1.75 \times q_t^{0.627}$	Clay	[61]
Shear wave velocity	$9.44 \times q_t^{0.435} \times e_0^{-0.532}$	Clay	[60]
Shear wave velocity	$1.75 \times q_t^{0.627}$	Clay	[60]

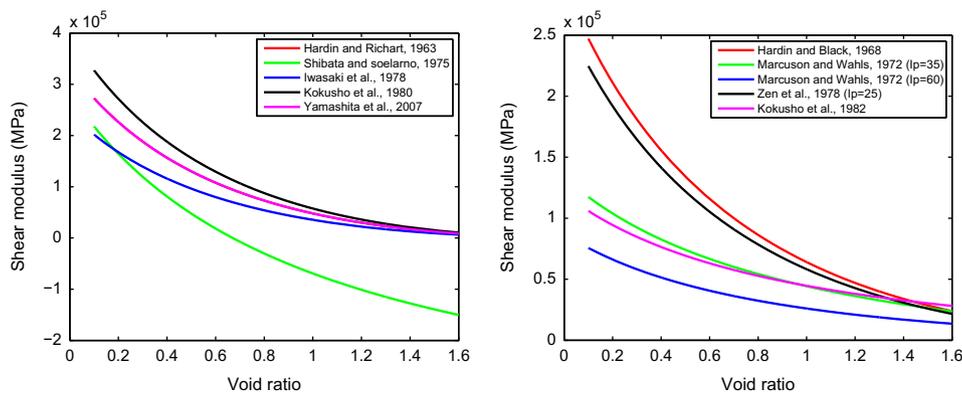


Fig. 11. Empirical void ratio correlations.

on Eq. (2), for a range of void ratios are shown in Fig. 11. I_p is the plasticity index associated with each sample. The effective confining stress for each relationship was assumed to be 100 kPa.

Eq. (2) depends solely on the prior calculation of void ratio and therefore is often used due to its ease of application. Alternatively, researchers have presented formulations which depend on additional experimentally calculated variables. For example, [54] outlined a correlation based upon liquid limit and undrained shear strength. Also, Ref. [30] presented a correlation based upon both void ratio and over-consolidation ratio (OCR). Despite this OCR is difficult to accurately determine even through lab testing thus making it difficult for practical use. Some empirical relationships for calculating OCR from CPT results are provided by [58].

Damping can also be calculated from classical lab test results with [52] suggesting it can be calculated using the hysteresis loop for a soil. Alternatively, several authors propose that damping is highly correlated with normalised shear modulus. As discussed previously, vibrations generated due to train passage are in the small strain zone thus allowing [40] to propose the relationship:

$$D = 0.0065(1 + e^{-0.0145I_p^{1.3}}) \quad (3)$$

This equation is based on solely the plastic modulus (I_p) and has been shown by [5] to provide an accurate approximation for a range of soils. Alternative formulations have also been presented by [68,44], both based on using cyclic shear strain values. Furthermore, [34] presented typical damping values for soil (Fig. 12).

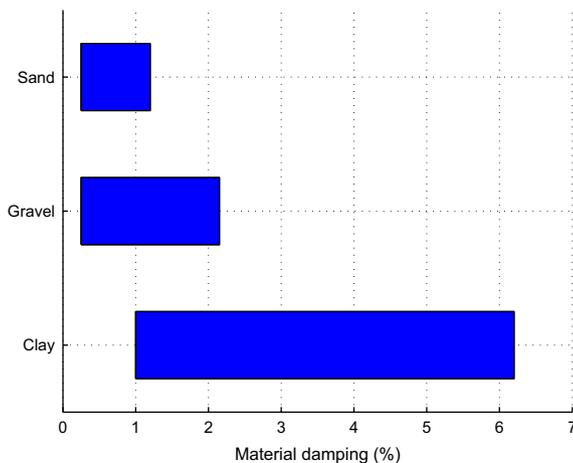


Fig. 12. Typical damping ratios (replicated from [34]).

4.4. Soil layer mapping

The scoping model was only capable computing a discrete number of input soil layers (2 layers), however typical soil profiles consist of a greater number of layers. Therefore, to enable the model to be used at any test site, the soil property input information was converted into a 2 layer soil. This translation was performed using a straightforward thickness weight average technique (Fig. 13):

$$E_{eq} = \frac{\sum H_i E_i}{\sum H_i} \quad (4)$$

where E_{eq} =equivalent Young's modulus, H_i =each layer thickness and E_i =Young's modulus of each layer.

5. Structural vibration, mitigation and excitation factors

The machine learning approach allowed for rapid prediction of ground vibrations in two layered soils. Additionally, the empirical soil relationships allowed for historical soil relationships to be included in the vibration propagation path. Despite this, the upgraded machine learning approach was based upon results obtained from a generic high speed train-track-soil interaction model, and thus only predicted absolute vibration levels on a soil surface (rather than in structures).

To upgrade ScopeRail versatility from the previously developed approach [14], and make it applicable to a wider range of track forms and excitation mechanisms, it was combined with empirical modification factors [24]. These factors allowed for the vibration level to be modified to account for elevated excitations generated due to wheel flats, corrugated track and switches/crossings. Similarly, the factors allowed for the vibration levels to be modified to account for ballast mats, floating slabs, resilient fasteners/ties and earthworks profiles. Although more detailed structural factors have been proposed [2], the use of transfer functions within a scoping model adds undesired complexity. Furthermore, because the [24] amplification factors were essentially uncoupled, and the vibration metric (VdB) was the same as that used within ScopeRail, the compatibility between methods was high. This facilitated a seamless coupling between the factors and ScopeRail.

Furthermore, as the original FE model was only used to predict ground surface vibration levels rather than building vibrations, the basic ScopeRail model could also only predict ground vibration levels. This is a commonly used approach [57,51,46,72,27,3,17,63] due to the difficulties in determining soil-building coupling characteristics. Although several attempts have been made to include soil-structure coupling within predictions [25,37], these methods are still experimental. To convert the ScopeRail predicted ground vibration levels to structural vibration and in-door noise, empirical modification factors were again used [24].



Fig. 13. Left: 'Mons 2012' test site, Right: 'HS1 2012' test site.

It should be noted that the factors related to train speed, distance from the track and geological conditions were not retained from the [24] procedure. This is because these factors were inherently included within the ScopeRail model. The final factors implemented with ScopeRail are shown in the Appendix.

6. Model validation

6.1. Field work

To ensure that the scoping model was capable of predicting vibration levels for a variety of test sites and that it had not been over-fitted, it was validated using three sets of experimental results. To provide a fair comparison, these field test results were composed of data collected by the authors and also by independent researchers.

The first set of results were recorded in Belgium in 2001 [18] and thus denoted 'Degrande 2001'. During testing, vibration levels were sampled using accelerometers and then converted to velocity time histories. A more detailed experimental description is found in the original article.

An experimental campaign was also undertaken in 2012 to collect results for the additional comparisons. First, vibrations were recorded on the Paris to Brussels high speed line [12,48,13] and were denoted 'Mons 2012'. Second, vibrations were recorded on the London–Paris high speed line (HS1) and were denoted 'HS1 2012'. Identical equipment was used for both experimental tests, however for the 'Mons 2012' tests, vibrations were measured up to 100 m from the track, while for the 'HS1 2012' tests, vibrations were measured up to 35 m from the track (Fig. 13). For both tests a multi-channel analysis of surface waves procedure was used to determine the underlying soil properties (Fig. 14). For each train passage the train speed was determined during post-processing using a combination of cepstral analysis, dominant frequency analysis and a regression analysis to compare experimental and theoretical frequency spectrum [49].

6.2. One layer model validation

First the model was tested using a homogenous soil to approximate the layered profile at each test site. To benchmark the model performance against a scoping model that did not include soil properties in its calculation, the results were compared to predictions calculated using the [24] approach.

Fig. 15 shows that the homogenous model performed well and was able to predict VdB values with strong accuracy for each test site. For the Mons 2012 test site ScopeRail closely matched the experimental results. Similar results were found for Degrande 2001 although there was an over prediction of vibration levels for the receivers at distances greater than 10 m. For the HS1 2012

results the new model was found to slightly over predict vibration levels at distances less than 20–25 m from the track, and to over predict levels at further distances.

A comparison between models revealed that performance was relatively similar, with both models overestimating vibration levels for the majority of receiver locations. For the [24] calculations, this reflects the anticipated conservative nature of the model. For the Mons 2012 results, ScopeRail was found to offer marginally enhanced performance at large offsets (2–3 dB), and moderately better accuracy for HS1 2012.

6.3. Two layer model validation

The two layer ScopeRail model was also tested against the experimental data and the [24] approach. Fig. 16 shows that again both models over-predicted vibration levels. Despite this, ScopeRail performed with increased accuracy in comparison to when the homogenous soil profile was used. This is particularly clear for the Degrande 2001 results where a significant improvement is obtained (up to 9–10 dB). For the Mons 2012 results enhanced accuracy was also found.

In comparison to the [24] approach, ScopeRail was found to outperform it for the Mons 2012 and Degrande 2001 test sites, however performance was still low for both models at the HS1 2012 site. This increase in accuracy was attributed to the additional degrees of freedom available within the 2-layer ScopeRail model.

6.4. Discussion

ScopeRail was found to offer strong vibration prediction performance, particularly when the 2-layer soil model was used. Prediction accuracy was highest for the Mons 2012 and Degrande 2001 test sites because the change in vibration levels with distance was relatively uniform, thus making these sites more straightforward to predict. In comparison, the HS1 2012 data set contained vibration levels with large amplitude unexpected local increases. It was challenging for the numerical model to predict these anomalies, however the scoping model was able to generate results that corresponded well to a best-fit line through the results. Therefore, it was concluded that the new model offered improved performance in comparison to [24].

7. Conclusions

A tool designed for the scoping assessment of in-door noise caused by high speed train passage was developed. First, a three-dimensional numerical model capable of simulating vibration generation and propagation from high speed rail lines was outlined. This model was executed many times, each time using a different combination of input parameters, to create a database of

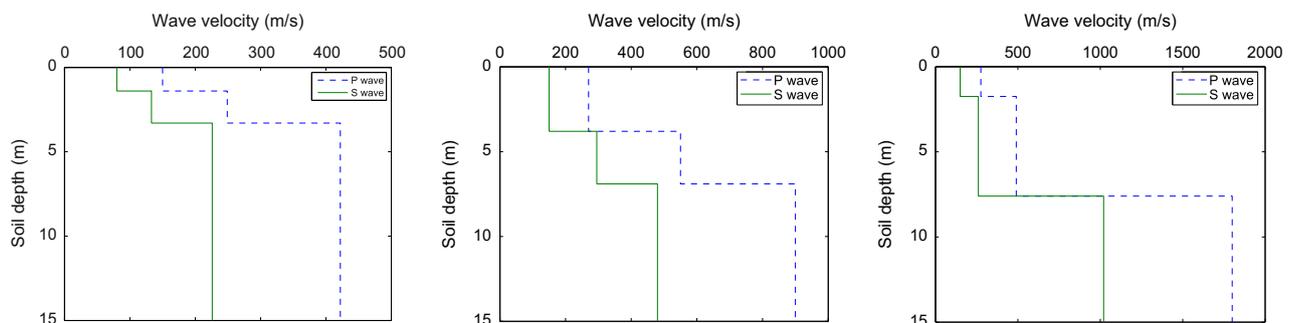


Fig. 14. Compressional and shear wave profiles at test sites, Left: Degrande 2001, Middle: Mons 2012, Right: HS1 2012.

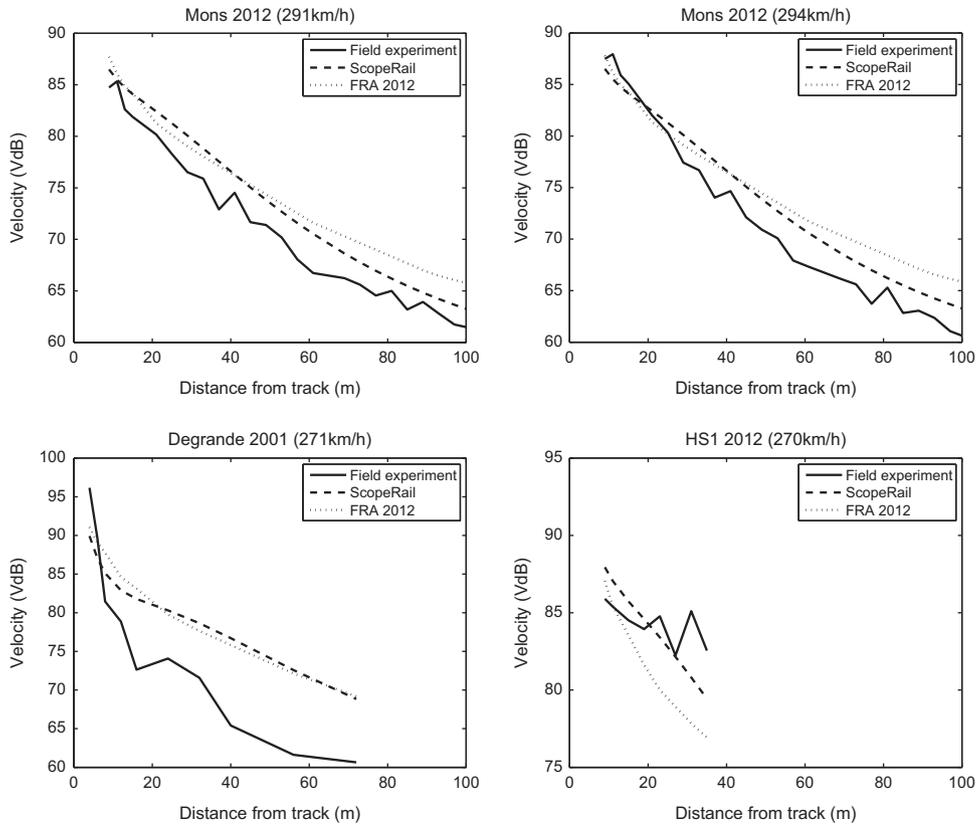


Fig. 15. One layer model performance, Top left: Mons 2012 (291 km/h), Top right: Mons 2012 (294 km/h), Bottom left: Degrande 2001 (271 km/h), Bottom right: HS1 2012 (270 km/h).

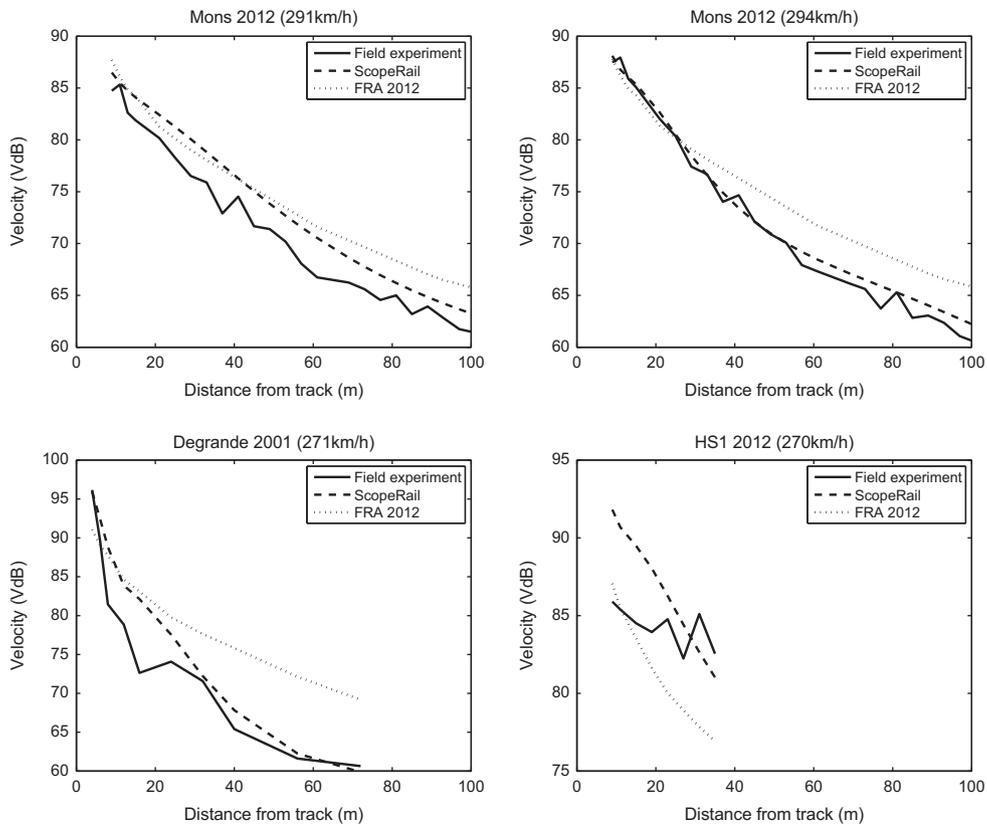


Fig. 16. Two layer model performance, Top left: Mons 2012 (291 km/h), Top right: Mons 2012 (294 km/h), Bottom left: Degrande 2001 (271 km/h), Bottom right: HS1 2012 (270 km/h).

results. These results were then analysed using a neural network approach to determine the effect of parameter changes on vibration levels. This resulted in a model that could instantly predict ground vibration levels in the presence of different train speeds and soil profiles. Finally, a collection of empirical factors were added to the model to facilitate the prediction of structural vibration and in-door noise in buildings located near high speed lines. The final model is called ScopeRail and was shown to offer increased accuracy over an alternative scoping model.

The advantage of this increased accuracy is that it reduces the probability of under and over prediction of vibration levels. If levels are over predicted then unnecessary detailed vibration assessments will be needed for further analysis. If levels are under predicted then abatement measures may be required post line construction. Therefore higher accuracy predictions can result in substantial cost savings.

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Appendix

See Tables A1–A3.

Table A1
ScopeRail source factors (replicated from [24]).

Source factor	Adjustment to ScopeRail results
Worn wheels of wheel flats	+ 10 dB
Worn or corrugated track	+ 10 dB
Crossovers or other special track work	+ 10 dB

Table A2
ScopeRail track factors (replicated from [24]).

Track factor	Adjustment to ScopeRail results
Floating slab track bed	– 15 dB
Ballast Mats	– 10 dB
High resilience fasteners	– 5 dB
Resiliently supported sleepers	– 10 dB
Type of track structure (relative to at-grade tie and ballast)	
Aerial/Viaduct structure	– 10 dB
Embankment	0 dB
Open cutting	0 dB
Type of track structure (relative to bored tunnel in soil)	
Station	– 5 dB
Cut and cover	– 3 dB
Rock-based	– 15 dB

Table A3
ScopeRail receiver factors (replicated from [24]).

Receiver factor	Adjustment to ScopeRail results	
Coupling to building foundation	Wood frame	– 5 dB
	1–2 Story masonry	– 7 dB
	2–4 Story masonry	– 10 dB
	Large masonry (piled)	– 10 dB
	Large masonry (spread)	– 13 dB
	Foundation in rock	0 dB
Floor-to-floor attenuation	Storeys 1–5 above grade	– 2 dB per floor
	Storeys 5–10 above grade	– 1 dB per floor
Amplification due to resonances of floors, walls and ceilings	+ 6 dB	
Radiated sound	Typical at-grade track	– 50 dB
	Typical tunnelled track	– 35 dB
	Tunnel in rock	– 20 dB

References

- Andersen L, Nielsen SRK, Krenk S. Numerical methods for analysis of structure and ground vibration from moving loads. *Comput Struct* 2007;85(1-2):43–58. <http://dx.doi.org/10.1016/j.compstruc.2006.08.061>.
- Auersch L. Building response due to ground vibration—simple prediction model based on experience with detailed models and measurements. *Int J Acoust Vib* 2010;15(3):101–12.
- Auersch L. Train induced ground vibrations: different amplitude-speed relations for two layered soils. *Proc Inst Mech Eng Part F J Rail Rapid Transit* 2012;226(5):469–88. <http://dx.doi.org/10.1177/0954409712437305>.
- Baldi, G, Bellotti, R, Ghionna, V, Jamiolkowski, M, Presti, D. . Modulus of sands from CPT's and DMT's. In: 12th International conference on soil mechanics and foundation engineering; 1989. pp. 165–170.
- Biglari M, Ashayeri I. An empirical model for shear modulus and damping ratio of unsaturated soils. *Unsaturated Soils: Theory Pract* 2011;1:591–5.
- British Geological Association. (2013). Retrieved from (<http://www.bgs.ac.uk/>).
- Carels P, Ophalfens K, Vogiatzis K. Noise and Vibration evaluation of a floating slab in direct fixation turnouts in Haidari & Anthoupoli extensions of Athens metro lines 2 and 3. *Ingegneria Ferroviaria* 2012:533–52.
- Chebli H, Othman R, Clouteau D, Arnst M, Degrande G. 3D periodic BE–FE model for various transportation structures interacting with soil. *Comput Geotech* 2008;35(1):22–32. <http://dx.doi.org/10.1016/j.compgeo.2007.03.008>.
- Chin, C, Duann, S, Kao, T. . SPT-CPT correlations for granular soils. In: First international symposium on penetration testing; 1988. pp. 295–339.
- Connolly D, Giannopoulos A, Fan W, Woodward PK, Forde MC. Optimising low acoustic impedance back-fill material wave barrier dimensions to shield structures from ground borne high speed rail vibrations. *Constr Build Mater* 2013;44:557–64. <http://dx.doi.org/10.1016/j.conbuildmat.2013.03.034>.
- Connolly D, Giannopoulos A, Forde MC. Numerical modelling of ground borne vibrations from high speed rail lines on embankments. *Soil Dyn. Earthquake Eng* 2013;46:13–9. <http://dx.doi.org/10.1016/j.soildyn.2012.12.003>.
- Connolly, D.P. . High Speed Rail Dataset. Retrieved from (<http://www.davidpconnolly.com/>); 2014.
- Connolly, DP, Kouroussis, G, Fan, W, Percival, M, Giannopoulos, A, Woodward, P.K., et al. An experimental analysis of embankment vibrations due to high speed rail. In: Proceedings of the 12th international railway engineering conference; 2013.
- Connolly DP, Kouroussis G, Giannopoulos A, Verlinden O, Woodward PK, Forde MC. Assessment of railway vibrations using an efficient scoping model. *Soil Dyn Earthquake Eng* 2014;58:37–47. <http://dx.doi.org/10.1016/j.soildyn.2013.12.003>.
- Connolly DP, Kouroussis G, Laghrouche O, Ho C, Forde MC. Benchmarking railway vibrations—track, vehicle, ground and building effects (accepted paper). *Constr Build Mater—Special Issue: Railway Eng* 2014.
- Connolly, DP, Peters, J, Sim, A, Giannopoulos, A, Forde, MC, Kouroussis, G., et al. Railway vibration impact assessment—High accuracy and internationally compatible tool. In: Proceedings of the transportation research board 93rd annual meeting, Washington (USA); 2014.
- Costa PA, Calçada R, Cardoso AS. Ballast mats for the reduction of railway traffic vibrations. Numerical study. *Soil Dyn Earthquake Eng* 2012;42:137–50. <http://dx.doi.org/10.1016/j.soildyn.2012.06.014>.
- Degrande G, Schillemans L. Free field vibrations during the passage of a Thalys high-speed train at variable speed. *J Sound Vib* 2001;247(1):131–44. <http://dx.doi.org/10.1006/jsvi.2001.3718>.
- Dejong J. Site characterization—guidelines for estimating vs based on in-situ tests. *Soil interaction laboratory, UCDavis* 2007:1–22.
- Deutsches Institut für Normung. DIN 4150-2—human exposure to vibration in buildings. *Int Stand Organ* 1999:1–63.
- Dickensen, S. Dynamic response of soft and deep cohesive soils during the Loma Prieta earthquake of October 17, 1989. Ph.D. thesis. University of California; 1994.

- [22] El Kacimi A, Woodward PK, Laghrouche O, Medero G. Time domain 3D finite element modelling of train-induced vibration at high speed. *Comput Struct* 2013;118:66–73. <http://dx.doi.org/10.1016/j.compstruc.2012.07.011>.
- [23] Elias P, Villot M. Review of existing standards, regulations and guidelines, as well as laboratory and field studies concerning human exposure to vibration. Deliverable D1.4. (RIVAS) 2011:1–72.
- [24] Federal Railroad Administration. High-speed ground transportation noise and vibration impact assessment. U.S. Department of Transportation 2012:1–248.
- [25] Fiala P, Degrande G, Augusztinovicz F. Numerical modelling of ground-borne noise and vibration in buildings due to surface rail traffic. *J Sound Vib* 2007;301(3–5):718–38. <http://dx.doi.org/10.1016/j.jsv.2006.10.019>.
- [26] Fryba L. *Vibration of solids and structures under moving loads*. Groningen, The Netherlands: Noordhoff International Publishing; 1972; 1–524.
- [27] Galvin P, Romero A, Domínguez J. Fully three-dimensional analysis of high-speed train-track-soil-structure dynamic interaction. *J Sound Vib* 2010;329(24):5147–63. <http://dx.doi.org/10.1016/j.jsv.2010.06.016>.
- [28] Griffin M. A comparison of standardized methods for predicting the hazards of whole-body vibration and repeated shocks. *J Sound Vib* 1998;215(4):883–914. <http://dx.doi.org/10.1006/jsvi.1998.1600>.
- [29] Gupta S, Hussein M, Degrande G, Hunt HEM, Clouteau D. A comparison of two numerical models for the prediction of vibrations from underground railway traffic. *Soil Dyn Earthquake Eng* 2007;27(7):608–24. <http://dx.doi.org/10.1016/j.soildyn.2006.12.007>.
- [30] Hardin B, Black W. Vibration modulus of normally consolidated clay. *J Soil Mech Found Div* 1963;89:33–65.
- [31] Harris, Miller, Hanson. Summary of European high speed rail noise and vibration measurements (HMM report no. 293630-2) (pp. 1–158; 1996.
- [32] Hasancebi N, Ulusay R. Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments. *Bull Eng Geol Environ* 2006;66(2):203–13. <http://dx.doi.org/10.1007/s10064-006-0063-0>.
- [33] Hegazy, Y, Mayne, P. Statistical correlations between vs and CPT data for different soil types. In: (CPT'95), symposium on cone penetration testing; 1995. pp. 173–178.
- [34] Houbrechts J, Schevenels M, Lombaert G, Degrande G, Rucker W, Cuellar V, et al. Test procedures for the determination of the dynamic soil characteristics 2011:1–107 (RIVAS—Deliverable D1.1).
- [35] Hussein MFM, Hunt HEM. A numerical model for calculating vibration from a railway tunnel embedded in a full-space. *J Sound Vib* 2007;305(3):401–31. <http://dx.doi.org/10.1016/j.jsv.2007.03.068>.
- [36] Hussein MFM, Hunt HEM. A numerical model for calculating vibration due to a harmonic moving load on a floating-slab track with discontinuous slabs in an underground railway tunnel. *J Sound Vib* 2009;321(1–2):363–74. <http://dx.doi.org/10.1016/j.jsv.2008.09.023>.
- [37] Hussein M, Hunt HEM, Kuo K, Costa PA, Barbosa J. The use of sub-modelling technique to calculate vibration in buildings from underground railways. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* 2013. <http://dx.doi.org/10.1177/0954409713511449>.
- [38] Imai, T. P and S-wave velocities of the ground in Japan. In: Ninth international conference of soil mechanics and foundation engineering; 1977. pp. 257–260.
- [39] Imai, T, Tonouchi, K. . Correlation of N-value with S-wave velocity and shear modulus. In: Proceedings of the second European symposium of penetration testing; 1982. pp. 57–72.
- [40] Ishibashi I, Zhang X. Unified dynamic shear moduli and damping ratios of sand and clay. *Soils Found* 1993;33(1):182–91.
- [41] Ilysan R. Correlations between shear wave velocity and in-situ penetration test results. *Teknik Dergi* 1996;7(2):1187–99.
- [42] Jafari M, Shafiee A, Razmkhah A. Dynamic properties of fine grained soils in south of Tehran. *J Seismol Earthquake Eng* 2002;4(1):25–35.
- [43] Johnson K. *Contact mechanics*. Cambridge, UK: Cambridge University Press; 1985; 1–468.
- [44] Kagawa T. Moduli and damping factors of soft marine clays. *J Geotech Eng* 1993;118(9):1360–75.
- [45] Katou M, Matsuoka T, Yoshioka O, Sanada Y, Miyoshi T. Numerical simulation study of ground vibrations using forces from wheels of a running high-speed train. *J Sound Vib* 2008;318:830–49. <http://dx.doi.org/10.1016/j.jsv.2008.04.053>.
- [46] Kattis S, Polyzos D, Beskos D. Vibration isolation by a row of piles using a 3-D frequency domain BEM. *Int J Numer Methods Eng* 1999;728(February):713–28.
- [47] Kenney J. Steady-state vibrations of beam on elastic foundation for moving load. *J Appl Mech* 1954;76:359–64.
- [48] Kouroussis, G, Connolly, DP, Forde, MC, Verlinden, O. An experimental study of embankment conditions on high-speed railway ground vibrations. Bangkok, Thailand: International congress on sound and vibration; vol. 4, 2013, pp. 3034–3041.
- [49] Kouroussis G, Connolly DP, Forde MC, Verlinden O. Train speed calculation using ground vibrations. *Proc Inst Mech Eng Part F J Rail Rapid Transit* 2014;0(0):1–18. <http://dx.doi.org/10.1177/0954409713515649>.
- [50] Kouroussis G, Connolly DP, Verlinden O. Railway induced ground vibrations—a review of vehicle effects. *Int J Rail Transp* 2014;2(2):69–110. <http://dx.doi.org/10.1080/23248378.2014.897791>.
- [51] Kouroussis G, Verlinden O, Conti C. Free field vibrations caused by high-speed lines: measurement and time domain simulation. *Soil Dyn Earthquake Eng* 2011;31(4):692–707. <http://dx.doi.org/10.1016/j.soildyn.2010.11.012>.
- [52] Kramer S. *Geotechnical earthquake engineering*. Prentice Hall; 1996; 1–653.
- [53] Krylov V. Generation of ground vibrations by superfast trains. *Appl Acoust* 1995;44(2):149–64. [http://dx.doi.org/10.1016/0003-682X\(95\)91370-1](http://dx.doi.org/10.1016/0003-682X(95)91370-1).
- [54] Larsson, R, Mulabdic, M. . Shear moduli in Scandinavian clays; measurements of initial shear modulus with seismic cones—empirical correlations for the initial shear modulus in clay. In: Transport Research Board; 1991. pp. 1–127.
- [55] Lee C, Tsai B. Mapping Vs30 in Taiwan. *Terr Atmos Oceanic Sci* 2008;19(6):671–82. [http://dx.doi.org/10.3319/TAO.2008.19.6.671\(PT\)1](http://dx.doi.org/10.3319/TAO.2008.19.6.671(PT)1).
- [56] Lee S. Regression models of shear wave velocities in Taipei basin. *J Chin Inst Eng* 1990;13(5):519–1990.
- [57] Lombaert G, Degrande G. Ground-borne vibration due to static and dynamic axle loads of InterCity and high-speed trains. *J Sound Vib* 2009;319:1036–66. <http://dx.doi.org/10.1016/j.jsv.2008.07.003>.
- [58] Lunne T, Robertson P, Powell J. *Cone penetrating testing*. Spon Press; 1997; 1–312.
- [59] Mayne P. Undisturbed sand strength from seismic cone tests. *Geomech Geoenge* 2006;1(4):239–57.
- [60] Mayne P, Rix G. Gmax-qc relationships for clays. *ASTM Geotech Test J* 1993;16(1):54–60.
- [61] Mayne P, Rix G. Correlations between shear wave velocity and cone tip resistance in clays. *Soils Found* 1995;35(2):107–10.
- [62] Mulliken J, Rizos DC. A coupled computational method for multi-solver, multi-domain transient problems in elastodynamics. *Soil Dyn Earthquake Eng* 2012;34(1):78–88. <http://dx.doi.org/10.1016/j.soildyn.2011.10.004>.
- [63] O'Brien J, Rizos D. A 3D BEM-FEM methodology for simulation of high speed train induced vibrations. *Soil Dyn Earthquake Eng* 2005;25:289–301. <http://dx.doi.org/10.1016/j.soildyn.2005.02.005>.
- [64] Ohta Y, Goto N. Empirical shear wave velocity equations in terms of characteristic soil indexes. *Earthquake Eng Struct Dyn* 1978;6(2):167–87.
- [65] Paoletti, L, Hegazy, Y, Monaco, S, Piva, R. . Prediction of shear wave velocity for offshore sands using CPT data—Adriatic sea. In: Second international symposium on cone penetration testing. Huntington Beach, California; 2010. pp. 1–8.
- [66] Pitilakis K, Raptakis D, Lontzetidis K, T-V. Geotechnical and geophysical description of EURO-SEISTEST, using field, laboratory tests and moderate strong motion recordings. *J Earthquake Eng* 1999;3(3):381–409.
- [67] Robertson P, Campanella G, Wightman A. SPT-CPT correlations. *J Geotech Eng* 1983;109(11):1449–59.
- [68] Rollins K, Evans M, Diehl N, Daily W. Shear modulus and damping relationships for gravels. *J Geotech Geoenviron Eng* 1998;124(5):396–405.
- [69] Rossi F, Nicolini A. A simple model to predict train-induced vibration: theoretical formulation and experimental validation. *Environ Impact Assess Rev* 2003;23(3):305–22. [http://dx.doi.org/10.1016/S0195-9255\(03\)00005-2](http://dx.doi.org/10.1016/S0195-9255(03)00005-2).
- [70] Seed H, Idriss I, Arango I. Evaluation of liquefaction potential using field performance data. *J Geotech Eng* 1983;109:458–82.
- [71] Seed H, Wong R, Idriss I, Tokimatsu K. Moduli and damping factors for dynamic analyses of cohesionless soils. *J Geotech Eng* 1987;112(11):1016–32.
- [72] Sheng X, Jones CJ, Petyt M. Ground vibration generated by a harmonic load acting on a railway track. *J Sound Vib* 1999;225(1):3–28. <http://dx.doi.org/10.1006/jsvi.1999.2232>.
- [73] Sheng X, Jones CJ, Thompson DJ. A theoretical model for ground vibration from trains generated by vertical track irregularities. *J Sound Vib* 2004;272(3–5):937–65. [http://dx.doi.org/10.1016/S0022-460X\(03\)00782-X](http://dx.doi.org/10.1016/S0022-460X(03)00782-X).
- [74] Sheng X, Jones C, Thompson D. Prediction of ground vibration from trains using the wavenumber finite and boundary element methods. *J Sound Vib* 2006;293(3–5):575–86. <http://dx.doi.org/10.1016/j.jsv.2005.08.040>.
- [75] Sisman, H. . An investigation on relationships between shear wave velocity and SPT and pressuremeter test results. In: M.Sc. thesis. Ankara University; 1995.
- [76] Thornely-Taylor, R.M. . The prediction of vibration, groundborne and structure-radiated noise from railways using finite difference methods—Part I—Theory. In: Proceedings of the Institute of Acoustics; 2004. 26, pp. 1–11.
- [77] Tsiambaos G, Sabatakakis N. Empirical estimation of shear wave velocity from in situ tests on soil formations in Greece. *Bull Eng Geol Environ* 2010;70(2):291–7. <http://dx.doi.org/10.1007/s10064-010-0324-9>.
- [78] Vogiatzis K. Noise & Vibration theoretical evaluation & monitoring program for the protection of the ancient “Kapnikarea Church” from Athens Metro Operation. *Int Rev Civil Eng (I.R.E.C.E.)* 2010;1(5):328–33.
- [79] Vogiatzis K. Environmental ground borne noise and vibration protection of sensitive cultural receptors along the Athens Metro Extension to Piraeus. *Sci Total Environ* 2012;439:230–7. <http://dx.doi.org/10.1016/j.scitotenv.2012.08.097>.
- [80] Yang LA, Powrie W, Priest JA. Dynamic stress analysis of a ballasted railway track bed during train passage. *J Geotech Geoenviron Eng* 2009;135(5):680. [http://dx.doi.org/10.1061/\(ASCE\)GT.1943-5606.0000032](http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0000032).