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SOIL NON-LINEARITY ON HIGH SPEED RAILWAY LINES

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Abstract

Increases in operational train speed have resulted in an elevated probability that dynamic effects will occur inside the railway track and subgrade structure. This is problematic because it causes soil non-linearity, thus resulting in reduced soil stiffness. Therefore, this paper outlines a numerical semi-analytical frequency domain model to compute and analyse non-linear stiffness degradation below railway lines. An equivalent linear approach is used to incorporate non-linear stiffness and damping changes into a thin-layer element frequency-wavenumber domain formulation. The model is validated using published data and then used to analyse non-linearity. It is shown that non-linearity plays an important role in track-ground response, with track displacements increasing significantly in magnitude. It is also shown that the critical velocity can be reduced significantly, which is important because many high speed lines set their dynamic threshold at 70% of the linearly calculated value. Similar findings are made for track velocities and soil strain levels, thus indicating it is vital to consider soil non-linearity when modelling high speed rail track behaviour.

Keywords: Railway track dynamics, non-linear soil, thin-layer element method

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1 INTRODUCTION

Operational railway speeds have increased over the past 40 years since the inception of high speed rail. This means it is increasingly likely that trains will induce high levels of dynamics within the track-soil structure. This occurs when the trains peed approaches the natural wave speeds of the track-ground system. The speed at which maximum dynamic amplification occurs is the 'critical velocity' ([1], [2]). This is undesirable because it is a safety risk, increases track degradation and can induce ground-borne vibration ([3],[4], [5]).

To analyze critical velocity, early approaches modelled the problem analytically [6]. Then, with the aim of simulating more complex ground conditions (e.g. layered soil), integral transform methods [7] were proposed. To allow for the track to also be modelled in a more detailed manner, 'two-and-a-half' dimensional models (2.5D) were also developed ([8], [9], [10]). These assumed the track was invariant in the direction of vehicle travel, thus allowing the problem to be discretized in 2D. This provided greater model flexibility, while maintaining a relatively low number of degrees of freedom.

The majority of railway vibration models are formulated in the frequency-wavenumber domain, meaning they are typically limited to considering linearly elastic material behavior. This assumption is suitable for many situations, however limits the analysis of non-linearity's such as wheel-rail contact ([11]) and soil stiffness degradation. Soil stiffness degradation is particularly important on heavy haul and high speed rail lines were the elevated loads and high speeds can cause high strain levels. These strains can then reduce the soil stiffness by a significant percentage, thus causing higher track deflections.

To include non-linear material effects, [1] manually adjusted the soil shear wave velocity at different speeds to account for the reduced stiffness effect. A challenge with this approach is that manually choosing stiffness' values is open to error and difficult to apply over multiple soil regions. Therefore [12], [13] proposed 3D time-domain constitutive non-linear time domain formulations and validated results against field data recorded in Sweden. A challenge with this approach is that such models are computationally intensive and often require a large number of material input properties that are challenge to quantify.

As an alternative, [14] proposed the use of a frequency-wavenumber domain 2.5D finite/infinite element model which although was linear, used an iterative procedure implement non-linearity. Again the model was compared to the data recorded in Sweden and strong agreement was found but with reduced run times compared to the 3D constitutive approach.

This paper builds upon this iterative linear equivalent approach. Instead of a 2.5D model though, a semi-analytical approach is preferred because it further reduces run times thus allowing for larger sensitivity studied to be performed. The track is modelled analytical while the soil is modelling using the thin-layer element method. It is validated and then used to make findings into the effect of non-linearity of dynamic amplification curves.

2 NUMERICAL MODEL

The model uses a semi-analytical method to compute vertical track deflections. It consists of an analytical track model, and a semi-analytical thin-layer element model for the soil. These sub-models are formulated in the frequency-wavenumber domain, and then coupled assuming a relaxed boundary condition at their interface. To do so, although the 2 models have different numbers of degrees of freedom, they are only coupled in the vertical direction. As will be shown, this approach produce accurate results, yet allows for the simulation of deep-wave propagation in an efficient manner [15].

2.1 Track model

The track is modelled upon a generic slab track, using springs for the railpads and beam elements for the rail and slab (Figure 1). The equations of motion are formulated in the wave-number-frequency domain and shown in Equation 1. Further details of the track formulation are found in [15].

$$\begin{bmatrix} EI_r k_x^4 + k_p^* - \quad {}^2 m_r & -k_p^* \\ -k_p^* & EI_s k_x^4 + k_p^* - \omega^2 m_s + k_{eq} \end{bmatrix} \begin{Bmatrix} \tilde{u}_r(k_x,\omega) \\ \tilde{u}_s(k_x,\omega) \end{Bmatrix} = \begin{Bmatrix} \tilde{P}(k_x,\omega) \\ 0 \end{Bmatrix} \tag{1}$$

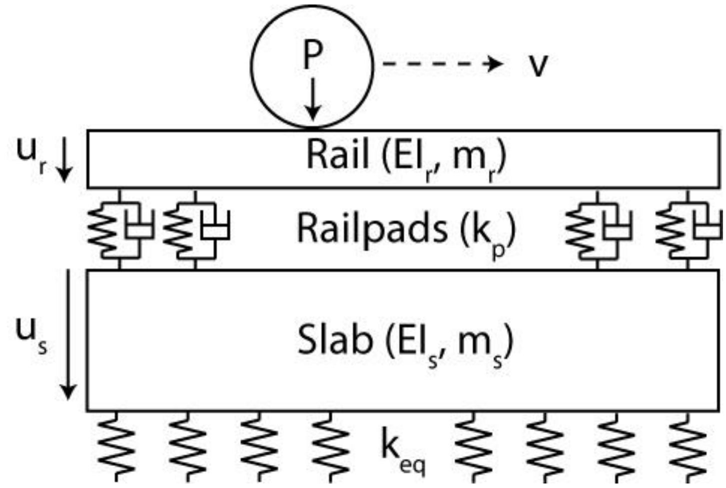

Figure 1: Track model

2.2 Ground model

The ground behavior is simulated using the thin-layer element method. First the soil stratum is discretized into a series of thin and horizontal elements, each with 3 nodes (Figure 2). This ensures that the stresses and strains are accurately reproduced, which is important for the linear equivalent updating procedure. Again, the equations of motion are formulated in the frequency-wavenumber domain as shown in Equation 2, where **K** and **M** are the global stiffness and mass matrices respectively, **U** is displacement, ω is frequency and **P** is the load.

$$([\mathbf{K}] - \omega^2[\mathbf{M}])\mathbf{U} = \mathbf{P} \tag{2}$$

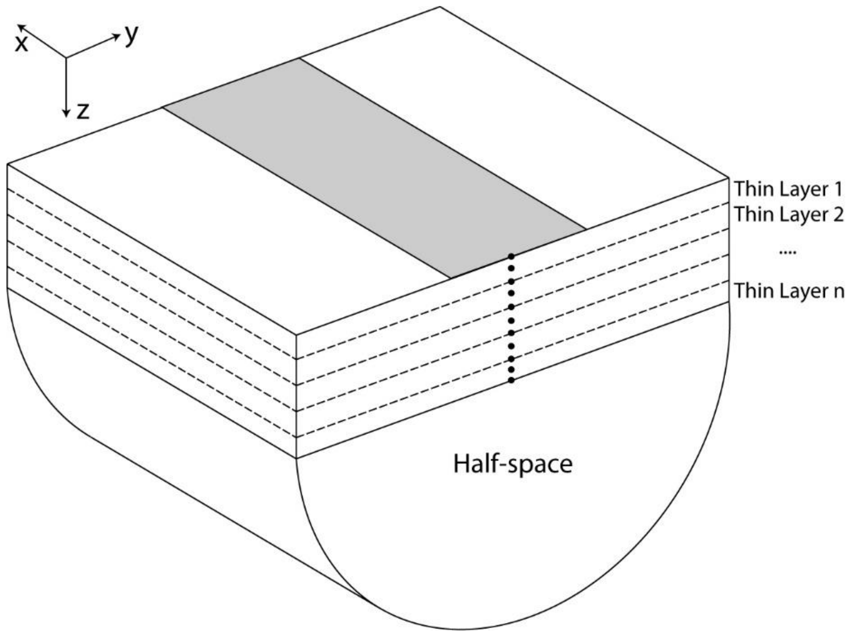

Figure 2: Soil model

2.3 Track-soil coupling

The track model and soil model are coupled using a frequency-wavenumber dependent stiffness. This is computed using the thin-layer method and assumes that there is an equilibrium of loads and a compatibility of displacements at the track-ground interface. It is important that the interaction across this boundary is accurately resolved because when the train speed nears the critical velocity there is very significant wave propagation within the soil stratum.

2.4 Linear equivalent implementation

At high train speeds, large strains can be induced in the underlying soil, causing a reduction in its stiffness, as illustrated in Figure 3. To capture this non-linear behaviour, a 'linear equivalent' approach is implemented.

This is useful because it can be implemented with frequency domain models, to approximate non-linear soil behavior in a much faster timeframe in comparison to time-domain constitutive models. By definition, it means that while the analysis remains linear, the soil properties are updated as function of the strain level, thus simulating non-linear type effects. It is implemented within the thin-layer formulation using the following steps:

- Low strain properties assumed for all thin-layer soil elements
- Strain time histories computed for all elements and determine effective octahedral shear strain values
- Use the maximum strain value to update the element stiffness, based upon stiffness-strain reduction curves (e.g. [14])
- Use the maximum strain value to update the element damping, based upon damping-strain reduction curves
- Repeat the above steps until convergence between consecutive iterations is below 3%

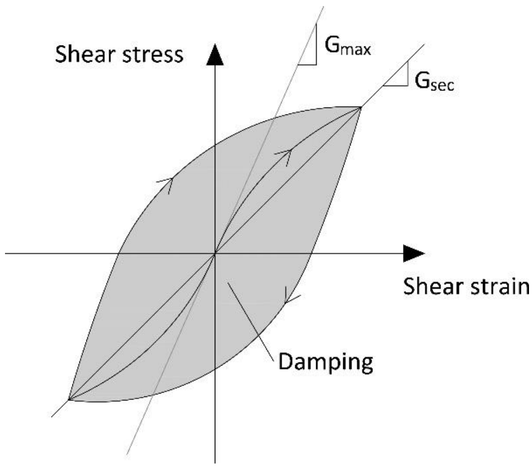

Figure 3: Stress-strain path

3 VALIDATION

The model was validated using field data recorded at Ledsgard, Sweden. This site was subject to large rail deflections and suspected high soil non-linearity during the passage of X2000 trains shortly after opening. This occurred because the track was constructed over soft ground, with a sandwiched layer of uncharacteristically soft organic clay. The detailed track and ground properties, including soil degradation curves, are given in [14], [16] and [17].

Figure 4 shows the time history response of the field the TLM signals at a train speed of 70 km/h. It is seen that the numerical model replicates the field result accurately in terms of magnitude and shape. The same is true for the faster speed of 180km/h, which is shown in Figure 5. Additional speeds were also computed with similar findings. Therefore is was concluded that the model was able to accurately predict track response in the presence of non-linear soil behavior.

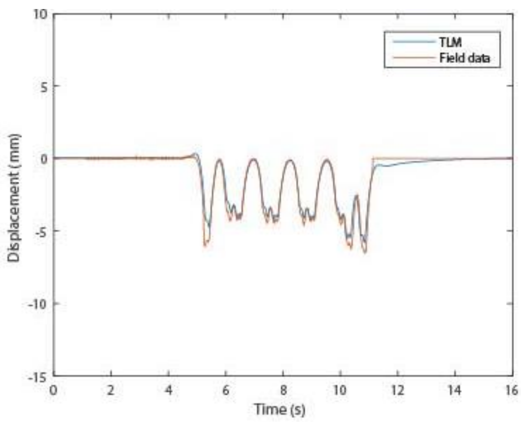

Figure 4: Displacement time history at 70km/h

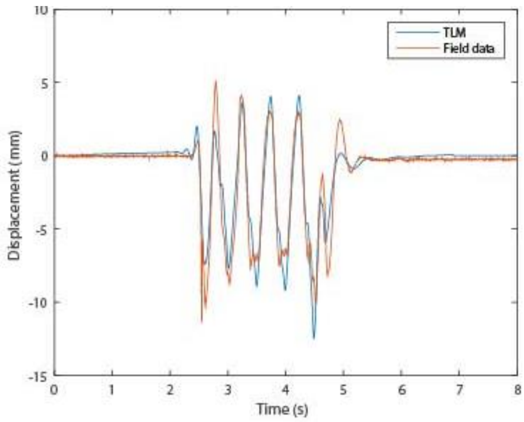

Figure 5: Displacement time history at 180km/h

4 NUMERICAL ANALYSIS

To investigate the role of soil non-linearity on high speed lines in more depth, an infinitely deep, homogenous soft soil was analysed. It had a small-strain stiffness of 45MPa, a Poisson's ratio of 0.35, a density of 1800kg/m^3 and damping of 0.03. The stiffness and damping degradation curves were identical to those used for the validation case. The vehicle was a single 18 tonne axle load moving at speeds ranging between 10-140m/s.

Figure 6 shows the rail dynamic amplification curve across the full speed range. It is seen that the linear and linear-equivalent curves have similar shape. The linear response yields lower displacements at the majority of speeds, except around its critical velocity peak at 90m/s. Further, the linear equivalent case has 29% higher maximum rail deflections compared to the linear case. Also, the critical velocity for the non-linear case reduces by 21% compared to the linear case. Both the change in deflection magnitude and critical speed are due to the drop in soil stiffness below the moving load, thus allowing the track to deflect more. However, it should be noted that the result is for a single wheel and that non-linearity is highly sensitive to multiple-wheel spacing and loading magnitude.

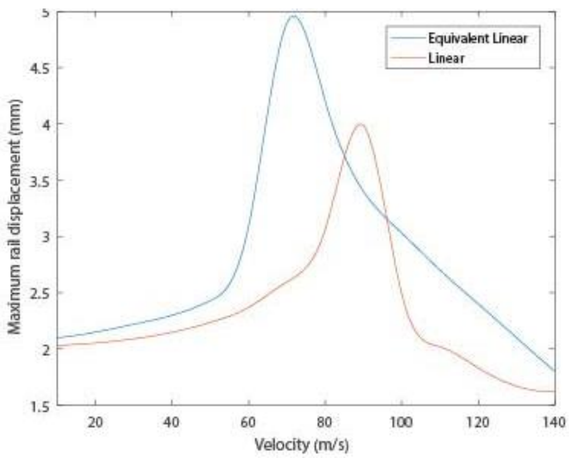

Figure 6 – DAF curves for linear and non-linear behavior

Finally, Figure 7 shows the effect of vehicle speed on strain levels with depth. Two speeds are shown: 10m/s (well below the critical speed) and 70m/s (at the linear equivalent critical speed). It is seen that the maximum strains occur for both speeds close to 1m below the soil surface. However, at all depths, the maximum octahedral strains are significantly lower for the linear case. This is the primary cause of the reduction of soil stiffness and the ultimate increase in rail deflections.

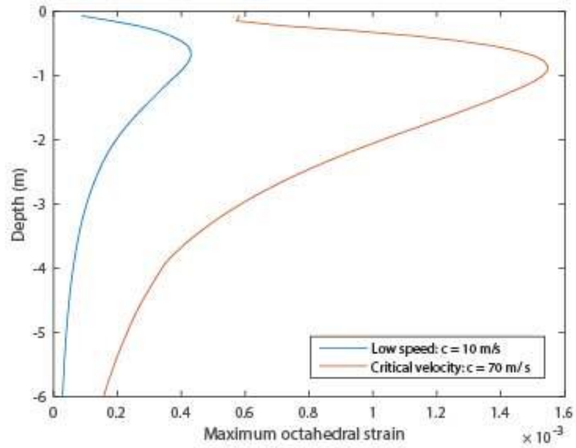

Figure 7 – Strain versus depth for linear and non-linear behavior

5 CONCLUSIONS

This paper presented a wavenumber-frequency domain model to predict railway track displacements in the presence of non-linear soil stiffness degradation. Analytical expressions were used for the track and the soil was simulated using the thin-layer method. Linear equivalent soil behavior was implemented using an iterative procedure where the soil strains were calculated during train passage and then used to update the stiffness and damping material properties. The model was validated using field data collected on a railway line with high non-linearity in Sweden. Finally, the model was used to investigate the effect of non-linearity on a homogenous half-space. It was found that the linear equivalent approach showed yielded significantly higher deflections compared to the linear case and that the critical speed was also lower.

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