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The effect of non-linear soil behavior on mixed traffic railway lines

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ABSTRACT: Railway freight services can be added to lines that have previously only be used for passenger services, with the aim of increasing network capacity. Freight trains have larger axle loads and thus can have a negative effect on track longevity, particularly on ballasted lines supported by sub-optimal ground conditions. This is because larger subgrade strains are generated, which can result in non-linear behavior. Therefore it is important to be able to determine the effect of the new rolling stock on track behavior before operation. This is challenging to do because non-linear soil behavior is challenging to simulate. As a solution, this paper presents an equivalent non-linear, thin layer element soil model, coupled to an analytical track model. It is capable of quickly and accurately computing the response of non-linear track behavior. The model is used to investigate the effect of introducing freight wagons on an existing ballasted passenger line with poor ground conditions.

1 INTRODUCTION

Railway operators who wish to tweak network capacity, may add freight services to tracks that have previously only be used for passenger services. If these lines were designed without freight in mind and/or were constructed at a time when compaction techniques were less scientific than today, then freight trains potential could have a detrimental impact.

To investigate and predict the track performance and ground response under various train loads and speeds, a number of modelling techniques have been proposed. The approaches include analytical models (Krylov 1995, Degrande & Lombaert 2001, Takemiya & Bian 2005), semi-analytical models (Sheng et al. 1999, Madshus & Kaynia 2000, Sheng et al. 2003, Kaynia et al. 2000, Thompson 2008, Triepaischajonsak & Thompson 2015). There are also numerical models: 2.5D models (Yang et al. 2003, Alves Costa et al. 2012, Alves Costa et al. 2010) and fully 3D models using finite element (FE) and possibly boundary element (BE) theories (Hall 2003, Kouroussis et al. 2011, Arlaud et al. 2015, Kacimi et al. 2013).

For freight trains, the dominant frequency components of the vibration are within 4-30 Hz (Jones & Block 1996). In order to study the vibrations induced by the freight trains, both dynamic and quasi-static generation mechanism, a track response model combined with transfer functions from sleeper to ground was utilized by (Jones & Block 1996). Another numerical model was proposed for the studies of longitudinal dynamics of the trainset (Belforte et al. 2008). On-site tests can be costly (Jones 1994), meaning theoretical models are often used to examine the track performance and ground response from freight trains.

In modelling the ground vibrations from railways, linear elastic models of the soil are commonly used, because strains are small. Nonetheless, when axle loads increase and/or the train speed gets close to the critical velocity, the track deflections increase and non-linear soil response occurs (Madshus & Kaynia 2000, Alves Costa et al. 2010). To simulate this non-linear behavior, soil stiffness' can be artificially reduced (Madshus & Kaynia 2000, Kaynia et al. 2000). Alternatively, using an automated, equivalent non-linear approach, the shear modulus can be adjusted based on the maximum effective octahedral shear strain in each soil element. Then it can be updated element by element until a tolerance requirement is met (Alves Costa et al. 2010).

This paper therefore provides a robust and efficient semi-analytical approach to model non-linear soil effects. The track is modelled analytically and allows for 1D wave propagation. The soil is modelled using a non-linear equivalent thin-layer method (TLM). The soil stiffness is updated in an iterative manner to simulate the non-linear behavior of the soil with the minimum computational effort.

2 NUMERICAL MODEL DEVELOPMENT

Freight trains carry heavier loads than passenger trains, thus causing elevated strains within the supporting subgrade. Large strains cause non-linear soil behavior, resulting in reduced support stiffness. To model this in a computationally efficient manner, a thin-layer finite element model was developed, and then combined with an equivalent non-linear procedure. To simulate the combined track-soil behavior, the track was coupled to the surface of the soil model.

2.1 Track model

Ballasted track was modelled as shown in Figure 1. One dimensional wave propagation was considered in the ballast and an equivalent spring was used to couple the track to the soil using (Dieterman & Metrikine 1996):

$$\begin{bmatrix} a_{11} & a_{12} & 0 \\ a_{21} & a_{22} & a_{23} \\ 0 & a_{32} & a_{33} \end{bmatrix} \begin{Bmatrix} \tilde{u}_r(k_1,\omega) \\ \tilde{u}_s(k_1,\omega) \\ \tilde{u}_{bb}(k_1,\omega) \end{Bmatrix} = \begin{Bmatrix} \tilde{P}(k_1,\omega) \\ 0 \\ 0 \end{Bmatrix} \quad (1)$$

$$a_{11} = EI_r k_1^4 + k_p^* - \omega^2 m_r \quad (2)$$

$$a_{12} = a_{21} = -k_p^* \quad (3)$$

$$a_{22} = k_p^* + \frac{2\omega E_b^* b\alpha}{\tan(\frac{\omega h}{C_p})C_p} - \omega^2 m_s \quad (4)$$

$$a_{23} = a_{32} = \frac{-2\omega E_b^* b\alpha}{\sin(\frac{\omega h}{C_p})C_p} \quad (5)$$

$$a_{33} = \frac{2\omega E_b^* b\alpha}{\tan(\frac{\omega h}{C_p})C_p} + k_{eq} \quad (6)$$

Where EI_r is the bending stiffness of the rail; m_r is the mass of rails per meter; m_s is the equivalent distributed mass of sleepers; k_p^* is the complex stiffness of the railpad; k_{eq} is the equivalent stiffness of the ground; E_b^* is the Young's modulus of the ballast; C_p is the compression wave speed in the ballast; h is the ballast layer height; α is the adimensional parameter, taken as 0.5; b is the half-width of the track.

The ballasted track model included the coupling between the track and the soil, using the ratio between the load and average displacement along the track-soil interface (Steenbergen & Metrikine 2007). It was calculated as:

$$\tilde{k}_{eq}(k_1,\omega) = \frac{2\pi}{\int_{-\infty}^{+\infty} \tilde{u}_{ZZ}^G(k_1,k_2,0,\omega)\frac{\sin(k_2 b)^2}{(k_2 b)^2}dk_2} \quad (7)$$

Where u_{zz} is the Green's function of vertical displacement of the ground in the wavenumber-frequency domain, and k_1 and k_2 are the Fourier images of coordinate x and y, respectively. The Green function was computed using the Haskell-Thompson approach (Sheng et al. 1999).

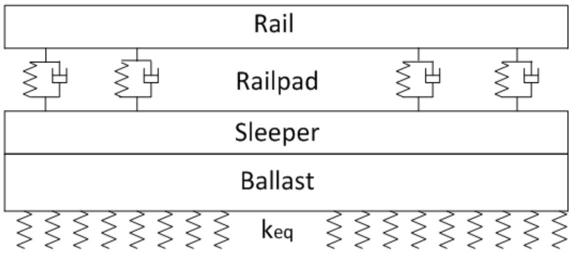


Figure 1. Analytical ballasted track model layout

2.2 Soil model

The soil was modeled using the Thin-Layer Method (TLM) as illustrated in the Figure 2.

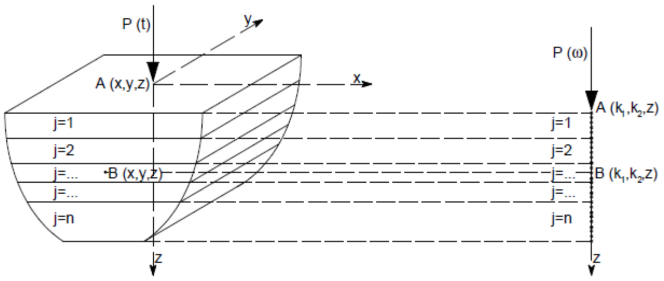


Figure 2. Schematic diagram of Thin-Layer Method modeling process (Alves Costa 2011)

It is worth noting that:

- The thickness of the thin layer quadratic elements were computed as h = wavelength/8 = $\pi/4k_{max}$, where k_{max} was the maximum wavenumber defined
- After obtaining the displacement of each node, the strains/stresses were calculated using Equations 8 and 9

$$\{\boldsymbol{\varepsilon}\} = [\mathbf{B}]\{\mathbf{u}\} \tag{8}$$
$$\{\boldsymbol{\sigma}\} = [\mathbf{D}]\{\boldsymbol{\varepsilon}\} = [\mathbf{D}][\mathbf{B}]\{\mathbf{u}\} \tag{9}$$

Where **[B] = [B₁ B₂ B₃]** and

$$[B_i] = \begin{bmatrix} ik_1N_i & 0 & 0 \\ 0 & ik_2N_i & 0 \\ 0 & 0 & \frac{\partial N_i}{\partial z} \\ ik_2N_i & ik_1N_i & 0 \\ 0 & \frac{\partial N_i}{\partial z} & ik_2N_i \\ \frac{\partial N_i}{\partial z} & 0 & ik_1N_i \end{bmatrix} \tag{10}$$

$$N_1(\xi) = \frac{1}{2}\xi^2 - \frac{1}{2}\xi$$
$$N_2(\xi) = 1 - \xi^2 \tag{11}$$
$$N_3(\xi) = \frac{1}{2}\xi^2 + \frac{1}{2}\xi$$

2.3 Equivalent non-linear model

If low stiffness soil is found on freight lines, it is likely to experience high levels of strain. This can result in soil stiffness degradation, thus increasing the track displacements and causing track deterioration. To simulate this, a non-linear equivalent mod-el, based on an iterative stiffness updating procedure, was used. This meant that each studied case was repeated multiple times until convergence was reached:

1) Assume low/zero strain within all elements
2) Use track-soil model to compute strain time histories and determine the maximum effective octahedral shear strain values for all elements
3) Use stiffness degradation curves (Figure 3), to obtain the new stiffness for all elements
4) Use damping curves, to obtain the new damping properties for all elements
5) Repeat steps 2 – 4 until the established tolerance is met for all elements (3% used in this case)

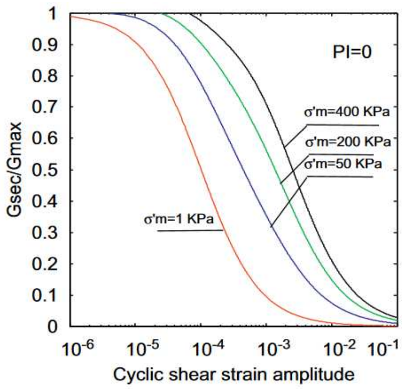


Figure 3. Modulus reduction curves for non-plastic soil (Alves Costa 2010)

3 MODEL VALIDATION

The model contained 3 main components: track, soil and the track-soil coupling mechanism. To ensure these were working correctly, validation was performed using an example outlined in (Chen et al. 2005). In order to validate the TLM model for the ground response, same case was studied and the stresses in the soil compared against the published result.

The train-embankment-ground model contained a Euler beam resting on top of the half-space with a concentrated moving force acting on the beam (Figure 4). The stresses generated by the contact force between the embankment and ground were calculated at 2m depth below the loading point.

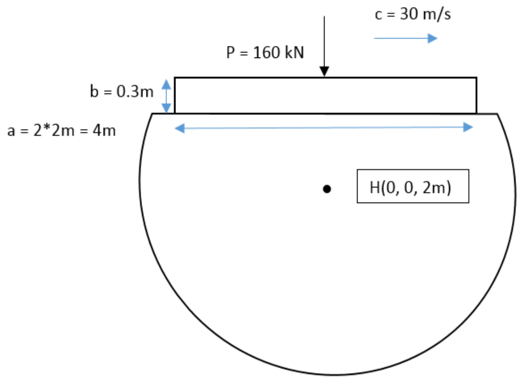


Figure 4. Schematic diagram of Chen et al. 2005 validation model

Key embankment and ground properties related to the validation are listed in the Table 1 and Table 2 respectively. The load was a vertical 160kN point load moving with a speed of 30 m/s.

Table 1. Properties of the embankment

Density (kg/m^3)	Young's modulus (MPa)	Width (m)	Height (m)	Mass (kg)	Second moment of area (m^4)
1900	30000	4	0.3	2280	0.009

Table 2. Properties of the ground

Shear modulus (MPa)	Poisson ratio	Density (kg/m^3)	Secondary wave speed (m/s)
10	0.45	1800	74.54

Figure 5 reveals strong agreement between the model and the benchmark.

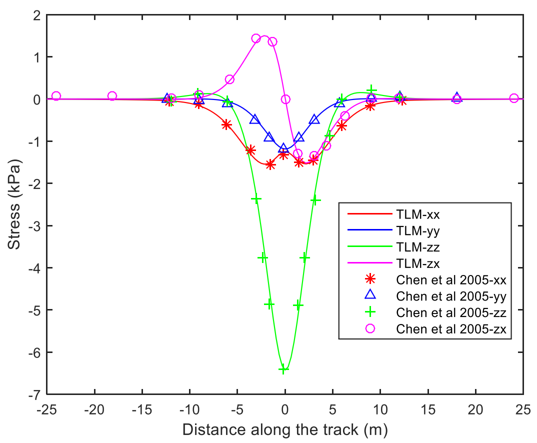
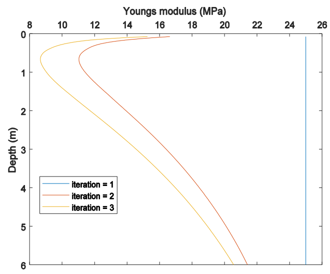
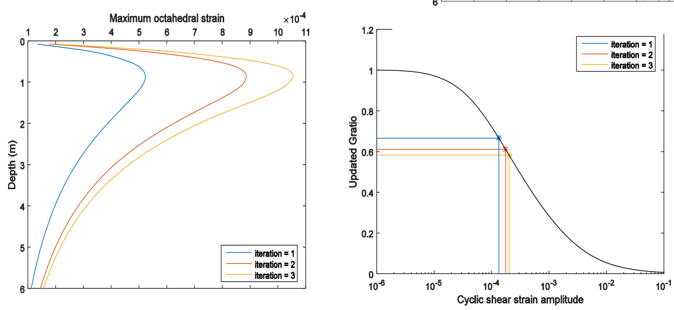


Figure 5. Comparisons of the dynamic stresses of an element with 2m depth underneath the moving load

4 ANALYSIS AND RESULTS

Simulations were run to determine the effect of adding 25 tonne fright axle loads to a previous passenger-only (17 tonne) ballasted line, with the aim of determining increases in track displacement and soil strain. To do so, the following track prop-





erties were assumed: m_r = 120 kg/m, m_s = 490 kg/m, $k_p{}^*$ = 5 × 10^8 N/m^2, $E_b{}^*$ = 125 MPa, h = 0.35 m, b = 2.5 m. The soil was modelled as a homogenous half-space using the following properties: density = 2000 kg/m^3, Young's modulus = 25 MPa, Poisson's ratio = 0.35, damping = 0.03. The stiffness degradation profile was the same as that shown previously. Train speed for both the passenger and freight axle loads was 26 m/s.

Figure 6 (left) shows the variation of strain versus depth within the soil. The maximum octahedral strains is located approximately 1 m below the ground surface and decays rapidly with depth.

Figure 6. Left: Octahedral strain vs soil depth; Right: Soil stiffness degradation during freight train passage

In comparison, Figure 6 (right) shows maximum strain and the resulting effect on soil stiffness. After the first iteration, the soil drops to 67% of its original stiffness and by the third (and final) iteration, it has reached a value of 59%.

The resulting reduction in stiffness (Young's modulus) with depth is shown in Figure 7 (left). For iteration 1, stiffness is constant with depth, however after strain updating, the subsequent iterations show large variations with depth, and are all lower than the starting value, particularly near the soil surface. For the passenger train, track displacements are 3.7 mm, however for the freight train, the linear value is 5.5 mm displacement, and the non-linear (iteration 3) is 8.4 mm. Therefore, it can be seen that the soil behavior is significantly non-linear, and that traditional linear analysis would greatly underestimate track deflections. This would result in much faster loss of track geometry and require frequent tamping. In addition, it is interesting to note that as the soil stiffness decreases, dynamic effects become more prevalent, with iteration 3 displacements appearing less symmetric than iteration 1.

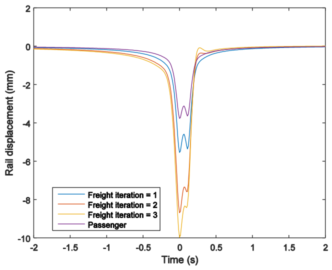


Figure 7. Left: Young's modulus reduction with depth; Right: Track displacements

5 CONCLUSIONS

There are increased pressures on network operators to run freight trains on ballasted track originally designed for passenger services. These tracks may not have the desired subgrade characteristics for heavy axle loads, possibly giving rise to non-linear soil behavior. To analyse this problem, an equivalent non-linear numerical model was developed, capable of quickly assessing soil stresses and strains, and resulting track displacements. The model was validated against a published benchmark case and then used to compare freight and passenger train response on a low stiffness ballasted line. It was shown that the track displacements have the potential to become high, due to non-linear stiffness reduction and the resulting dynamic amplification.

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