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Modelling railway track differential settlement for prediction of future deterioration and maintenance intervals

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Abstract

Under repeated traffic, railway track settles differently along the distance, causing irregularities in track geometry. This track irregularity evolves over time which induces higher train-track dynamic interaction force and further settlement. Track geometry is used to define track quality and maintenance required. Historical track geometry values can be extrapolated future track deterioration and maintenance intervals. However, using extrapolation of historical records become challenging when changes are made to rolling stock, traffic or track design. Therefore, this paper introduces a numerical algorithm that is capable of calculating differential settlement considering the incremental effect of train-track dynamic interaction forces and deviatoric stresses during the track lifecycle. The simulation is performed across frequency-wavenumber and time-space domains to optimise computational time and thus allow for track irregularity profile to be updated every load passage. The propagation 3D stress in track-ground is modelled explicitly using Finite

Element Method with Perfectly Matched Layers (FEM-PML) approach. A multi-body vehicle model combined with empirical settlement laws is used for train-track interaction and evolving track irregularity profile. After validating against the field data, the model is used to study the influence of increasing freight traffic on a passenger line. Three traffic scenarios are simulated: 100% passenger trains, adding 1 freight train per train and adding 2 freight trains per day. The results show that dynamic characteristics of the freight rolling stock have a significant effect on future deterioration rate and maintenance intervals. It is also highlighted the model's ability to predict future track deterioration when changes are made to rolling stock patterns.

Keywords: Railway track-ground settlement, differential settlement, train-track interaction, freight trains.

1 Introduction

Railway track geometry deteriorates differentially along the distance due to repeated dynamic train loading and different track support conditions [1], such as transition zones. Larger differential settlement causes higher irregularities in track geometry, inducing additional train-track dynamic interaction forces and further track deterioration. These track irregularities evolve with each load passage, thus changing the train-track dynamic interaction forces, track stress distributions and settlements over time.

The most commonly used indicator to describe the quality of track geometry for railway administrations is the standard deviation (SD) of vertical track geometry over a given distance [2]. When the SD value falls over a threshold limit, maintenance action (e.g. tamping) is required. To predict future track deterioration and maintenance intervals, historical track geometry data recorded at a given location is often used to extrapolate the future value [3]. However, this approach is logical for the prediction where no significant change is made on existing lines. In the situations where changes are made to the track (e.g. different track design or material properties) or rolling stock (e.g. freight or faster trains), historical changes in track geometry become less relevant to future track behaviour and thus difficult to use for extrapolation.

To address the aforementioned challenges, methodologies to predict differential track settlement without relying on historical track geometry records and consider the evolution of track geometry irregularities has been studied by [4]–[7]. However, it is challenging and computationally demanding to calculate the distributions of 3D dynamic stresses in the track and the ground when modelling over a larger number of cyclic loads in the time domain, particularly for large track structures [8]–[10]. These stress fields are used to compute the deviatoric stress which is one of the most influential parameters for settlement calculation [11] and thus needed to model explicitly.

This paper presents a novel numerical models that is capable of predicting future track geometry evolution and maintenance intervals, accounting for changes in rolling stock types. It is solved across frequency-wavenumber and time-space domain based on FEM-PML (Finite Element Method with Perfectly Matched Layers) approach combined with empirical settlement laws. The calculation of settlement is based upon the 3D stress fields in the track and ground considering its characteristics of stiffness nonlinearity [12], [13]. This optimised solution procedure allows rolling stock interactions to be replicated and minimises error in the calculation where the track geometry profile is recommended to be updated after every axle passage [14].

2 Methods

As outlined in Figure 1, the model is divided into two primary steps: Step I pre-calculation and Step II iterative process, solved across frequency-wavenumber and time-space domains. This modelling strategy updates the track geometry profile after every train passage, considering the evolution of stress fields in the track and the ground, and is thus capable of simulating changes to passenger-freight traffic ratios. The time-to-maintenance is calculated according to a given initial track profile and a threshold limit.

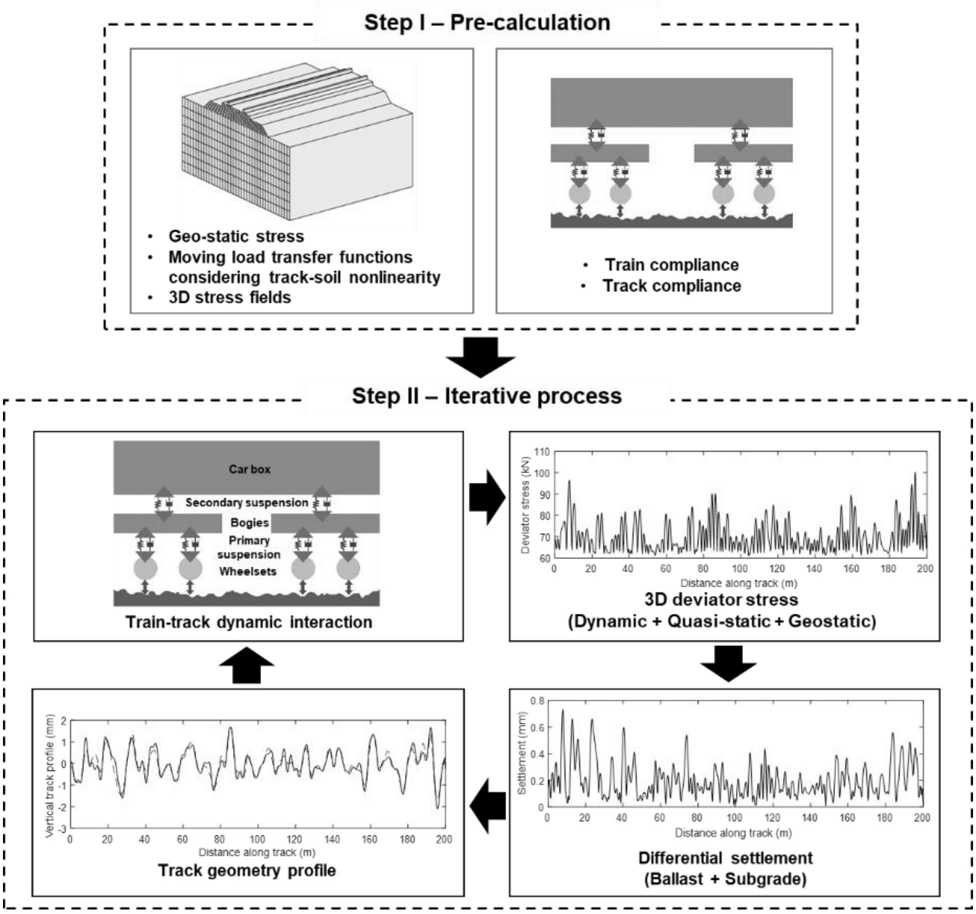

Figure 1 Model overview

In Step I, the geo-static stresses and the 3D elastodynamic response in the track and the ground are computed. The moving load transfer function considering non-linear effect in track-ground stiffness is computed in the frequency-wavenumber domain. The 3D stress transfer functions due to quasi-static and dynamic loading are then found. The track and vehicle compliance matrices for computing train-track dynamic interaction parameters are also prepared in advance. Step II is an iterative solver which is performed using a combination of wavenumber-frequency and space-time domains. Based on the track irregularity profile and the pre-calculated compliance matrices, the train-track dynamic interaction force is calculated using a multi-body model [15]. The total deviatoric stress which includes quasi-static, dynamic and geo-static responses is used to calculate settlements over the entire track length.based upon the empirical settlement models for ballast and subgrade. After every load passage, the vertical track geometry profile is updated and thus the train-track dynamic interaction force and corresponding deviatoric stress are recalculated. These subsequent steps are repeated until the SD of the vertical track profile exceeds a threshold limit or any specified condition. The description of numerical model in more detail can be found in [14].

The model is validated against historical track geometry data recorded from a selected UK track section, where the subgrade is silt (ML) with a shear strength of 25kPa. The traffic annual tonnage is 37 MGT (million gross tonnes) with the operational linespeed of 125mph. The track geometry data was recorded between January-2017 to December-2017 without tamping during the period. The track data recorded in January was used as the starting track irregularity profile and simulated until reaching the defined traffic. Figure 2 compares the predicted track geometry SD evolution from the simulation against the historical data records. This strong correlation confirms the model’s ability to accurately predict the evolution of irregularities in track geometry and SD.

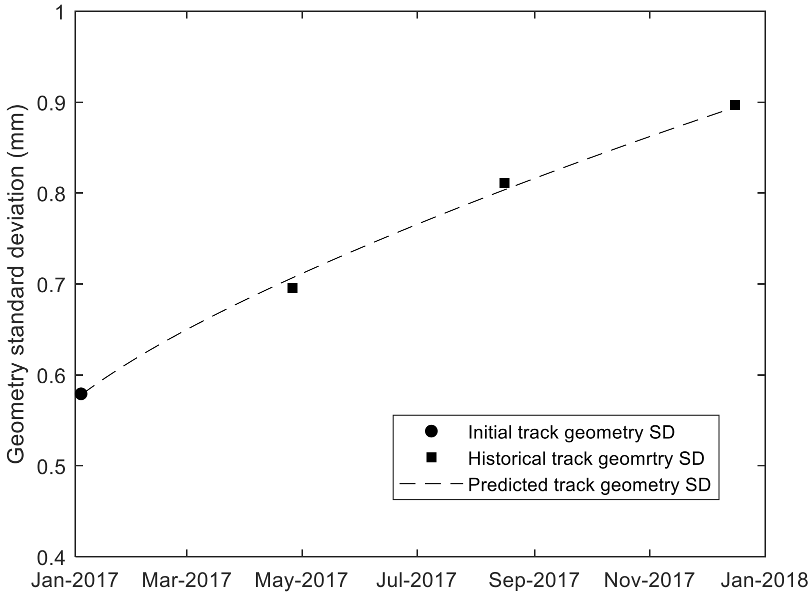

Figure 2 Evolution of vertical track geometry SD over time: predicted values vs historical data

3 Results

The validated model is used to analyse the effect of introducing freight traffic into a passenger line on maintenance intervals. Three scenarios are simulated: 100% passenger trains, adding 1 freight train per day, and adding 2 freight trains per day. The traffic volume per day is 0.054MGT for passenger trains. By adding 1 and 2 freight trains per day, the traffic volume per day increases by 0.004 and 0.008MGT respectively. The passenger train is an 11-car train with axle weight of 17 tonnes and moving speed of 125mph. The freight train is a 50-car train with axle weight of 27 tonnes and moving speed of 60mph. Table 1 summarises the properties of passenger train based upon Alfa Pendular taken from [15] and the freight train adapted from [17]. Figure 3 shows the finite element mesh of railway track, where the subgrade is lean clay with Young’s modulus of 70MPa and compressive strength of 250kPa.

Table 1 Mechanical properties of passenger and freight vehicles

Mechanical property	**Vehicle type**	
	Passenger	**Freight**
Car body mass (kg)	329×102	864×102
Car body pitching moment of inertia (kg.m2)	208×104	102×104
Bogie mass (kg)	4932	2800
Wheelset mass (kg)	1538	2000
Bogie pitching moment of inertia (kg.m2)	5150	2020
Primary suspension stiffness (kNm-1)	3420	-
Primary suspension viscous damping (Nsm-1)	360×102	-
Secondary suspension stiffness (kNm-1)	1320	2660
Secondary suspension viscous damping (Nsm-1)	360×102	25×102

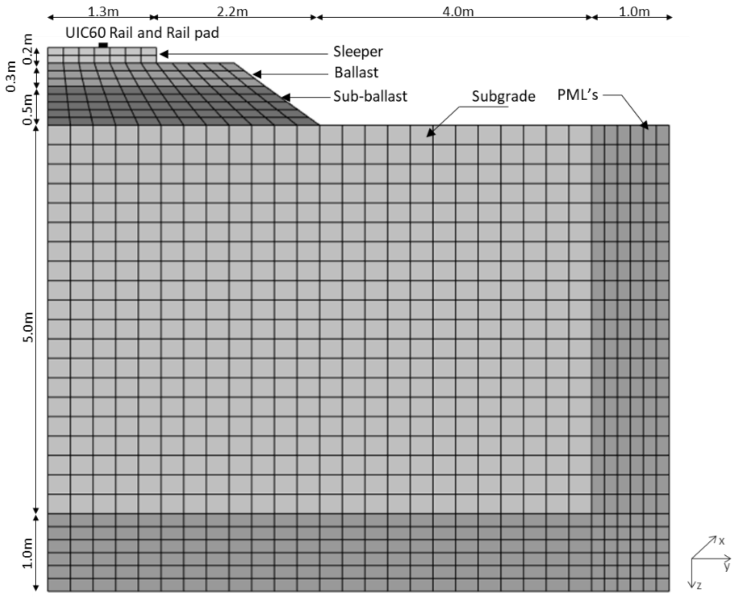

Figure 3 Finite element mesh of the investigated track model

The initial track geometry profile is artificially generated using the PSD function considering wavelengths between 3-35m, with the approximate starting SD of 1.7mm. Assuming the linespeed of 125mph, a SD threshold limit is set at 2.4mm. The evolving geometry SD curves over time from the initial SD value until the threshold limit value for three scenarios are compared in Figure 4. The durations until threshold exceedance for three scenarios are summarised in Table 2. The results show that the durations reduce by 9.0% and 13.6% when adding 1 and 2 freight trains per day respectively. Therefore, the dynamic characteristics of the freight vehicles have a significant influence on maintenance intervals.

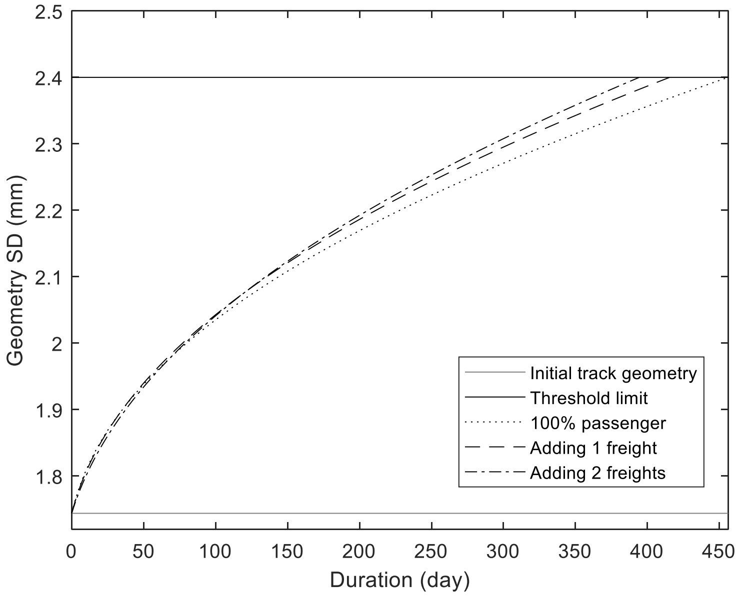

Figure 4 Track geometry SD curves over time for three scenarios

Table 2 Durations until threshold exceedance for three scenarios

Traffic scenario	Duration until threshold exceedance (days)	Percentage decrease
1. 100% passenger trains	456	0%
2. Adding 1 freight train per day	415	9.0%
3. Adding 2 freight trains per day	394	13.6%

4 Conclusions and Contributions

Track geometry helps quantify track quality and determine future maintenance requirements. Historical geometry records can be extrapolated to predict future deterioration and maintenance interval. However, historical data becomes irrelevant when changes are made to the rolling stock, timetable or track. Therefore, this paper presents a numerical model to compute differential track settlement considering the evolution of track geometry and predict future maintenance intervals. This model addresses several challenges: calculation of 3D stress fields in the track and ground considering its characteristics of stiffness nonlinearity; calculation of train-track interaction forces using a multi-body vehicle model; simulation of the evolution of track irregularities and dynamic forces; and simulation of the evolution of track-subgrade settlement laws. It is solved across frequency-wavenumber and time-space domain based on FEM-PML approach combined with empirical settlement laws. This optimised solution procedure allows for the track irregularities to be updated after every load passage, before applying the next load. It means that the train-track dynamic interaction forces and the corresponding deviatoric stresses are constantly evolved, thus allowing changes to be made to traffic conditions. The validated model is used to study the influence of increasing freight traffic on a passenger line. Three traffic scenarios, namely, 100% passenger train, adding 1 freight train per day and adding 2 freight trains per day are investigated. The results show that increasing freight traffic has a significant effect on the differential track settlement and maintenance intervals. It is also highlighted the model's ability to simulate when changes are made to the passenger-freight ratios on the existing line.

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