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On the Influence of Iterative Model Updating on Long-Term Differential Settlement in Ballasted Railway Tracks

J. C. O. Nielsen[1], B. Zuada Coelho[2], K. Nasrollahi[3] and D. Wong[4]

[1] Department of Mechanical Engineering/CHARMEC, Chalmers University of Technology, Gothenburg, Sweden
[2] Deltares, Safe and Resilient Infrastructure, 2600 MH Delft, The Netherlands
[3] Department of Architecture and Civil Engineering, Division of Structural Engineering, Chalmers University of Technology, Gothenburg, Sweden
[4] Deltares, Soil Water and Structures, 2600 MH Delft, The Netherlands

Abstract

Predicting differential track settlement and degradation of vertical track geometry (longitudinal level) remains a significant challenge for railway maintenance planning, particularly on lines with variable support conditions. This study compares two strategies for long-term settlement prediction in open ballasted railway tracks: a non-iterative approach based on a constant load spectrum, and an iterative approach in which the track model is updated as settlement evolves. Dynamic vehicle–track interaction analyses are performed using two independent numerical frameworks, from which maximum sleeper–ballast contact forces for each sleeper are obtained and used as input to empirical settlement models. The non-iterative approach assumes a fixed load distribution throughout the analysis, whereas the iterative approach captures the evolving track geometry and the associated redistribution of loads. The results show that both approaches yield similar overall settlement trends and spatial patterns. However, the iterative approach provides additional insight into load redistribution and the influence of evolving support conditions, which are important for assessing localised track behaviour. The comparison highlights when simplified non-iterative modelling is sufficient, as well as the added value of iterative analysis for representing long-term track behaviour.

Keywords: differential settlement, dynamic vehicle–track interaction, non-linear track model, iterative approach, ballasted track

1 Introduction

Accurate prediction of accumulated track settlement and the associated deterioration of vertical track geometry (longitudinal level) remains a critical challenge in railway infrastructure management. The need for reliable prediction methods is intensified by the continued growth in rail traffic. In Europe, passenger demand, measured in passenger-kilometres, nearly doubled between 1990 and 2019, while both passenger and freight traffic increased at an average annual rate of approximately 3% between 2015 and 2020 [1]. The resulting increase in traffic loading has accelerated infrastructure degradation and contributed to substantial maintenance and renewal backlogs, highlighting the need for predictive tools that support effective maintenance planning and intervention scheduling.

Track settlement is governed by the interaction between traffic loading, track structural characteristics, and the properties of the supporting ground [2]. Together, these factors control the rate and magnitude of long-term differential settlement and track geometry deterioration [3–6]. The deterioration of longitudinal level in ballasted track is commonly described by three stages: an initial bedding-in phase, a useful-life phase, and a wear-out phase [3]. Following construction, tamping, or renewal, rapid settlement occurs as the ballast densifies and the track structure stabilises. This is followed by a longer period of approximately linear deterioration under repeated traffic loading. Eventually, deterioration accelerates to a level at which maintenance interventions become too frequent to be economically viable. Models intended for long-term settlement prediction should therefore be capable of representing at least the first two stages of degradation.

Track settlement may be predicted using constitutive models [7], discrete element methods [8], or finite element (FE) models combined with empirical approaches [9, 11]. Constitutive models are typically implemented within FE frameworks, whereas discrete element methods explicitly resolve particle-scale interactions and heterogeneous deformation mechanisms. Although these approaches can capture differential settlement behaviour, they typically require extensive material characterisation and substantial computational effort, making long-term simulations computationally demanding. Empirical models offer a practical alternative and have demonstrated predictive capabilities comparable to more sophisticated numerical approaches while requiring fewer input parameters [9, 11]. However, many empirical models assume cyclic loading of constant magnitude, corresponding to a non-iterative prediction strategy, thereby neglecting the influence of evolving track geometry on vehicle–track interaction (VTI) forces and stress distributions. In reality, track geometry evolves as settlement develops, altering VTI forces and the resulting stress distributions within the track structure. To account for these interactions, the present study combines an empirical settlement model with a two-dimensional (2D) FE model and investigates the influence of an iterative prediction procedure on the long-term evolution of load magnitudes and differential settlement in open ballasted tracks.

Long-term differential track settlement under spatially variable support conditions is analysed using two independent modelling frameworks, ROSE and DIFF. Within each framework, both non-iterative (constant-load) and iterative prediction strategies are considered. This enables a systematic assessment of the influence of the chosen modelling framework and load-update strategy on differential settlement and track geometry degradation, while accounting for the inherently non-linear behaviour of ballast. In this context, the term iterative refers to the updating of track geometry and support conditions during the simulation, and should not be confused with the specific representation of non-linear support behaviour.

2 Modelling of dynamic vehicle–track interaction and track settlement

In this study, two independent modelling frameworks (ROSE and DIFF) are used for the prediction of long-term differential settlement in open ballasted railway tracks. In both frameworks, a vertical dynamic VTI analysis is first performed. The resulting distribution of maximum sleeper–ballast contact forces is then used as input to the empirical settlement models proposed by Nasrollahi et al. [5] (implemented in DIFF) and Varandas et al. [12] (implemented in ROSE).

The track is modelled using a 2D FE formulation that exploits longitudinal symmetry, such that only half of the vehicle–track system needs to be considered. The rail is represented by Euler-Bernoulli beam elements, while the sleepers are modelled as discrete masses spaced at 0.60 m intervals. In both the ROSE and DIFF frameworks, the track length is 120 m (200 sleeper bays), with rigid boundaries applied at the rail ends and at the base of each ballast spring–damper element. The selected model length and discretisation were verified to eliminate boundary effects. The combined stiffness and damping behaviour of the ballast and subgrade is represented by spring–damper elements beneath each sleeper (Figure 1), providing vertical support with linear or piecewise-linear, spatially varying stiffness. The train model consists of two loaded iron-ore wagons with a total of 10 degrees of freedom per vehicle. The axle load is 30 tonnes, and the loaded train operates at a speed of 60 km/h. Further details of the vehicle and track models can be found in [5,9]. The inputs for the model are collected in Table 1.

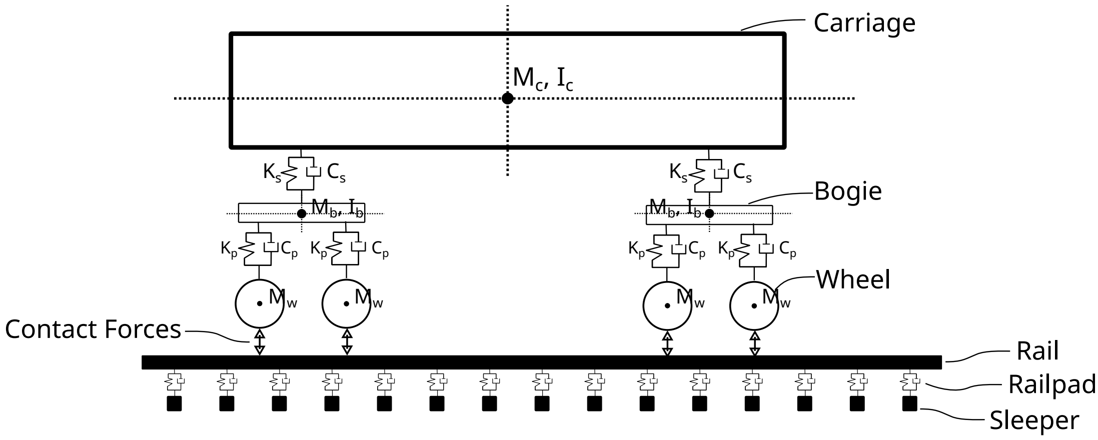


Figure 1: Schematic representation of the train–track interaction model. The sleepers are supported by spring–damper elements representing the ballast and subgrade, which may exhibit linear or piecewise-linear, and spatially varying (random), stiffness behaviour.

The ROSE framework [13] is implemented in Python and allows the evolution of track geometry to be captured in long-term simulations. The DIFF framework, implemented in MATLAB [10], is based on a similar formulation. Both frameworks can be applied using either non-iterative or iterative solution strategies. In addition, the DIFF framework allows for piecewise-linear support behaviour, whereas ROSE employs linear support elements while still accounting for evolving track geometry in the iterative procedure, as illustrated in Figures 2 and 3.

Two aspects are therefore considered in the modelling: the solution strategy (non-iterative or iterative) and the representation of support behaviour (linear or piecewise-linear). The present study primarily focuses on the influence of the solution strategy.

2.1 Iterative solution procedure

In the iterative scheme, short-term VTI is simulated using the static track displacement under gravity loading as the initial condition. The resulting load maxima at each sleeper–ballast interface, arising from the combined effects of static gravity loading and dynamic wheel passage, are extracted and used as input to an empirical settlement model. To represent the measured repetitive track response for successive vehicle passages reported in [14, 15], the load spectrum is restricted to the loads from the trailing bogie of the first vehicle and the leading bogie of the second vehicle.

The track model is then updated to reflect the evolving support conditions, including the possible presence of voided sleepers (considered only in DIFF) and state-dependent ballast and subgrade behaviour. Within each iteration, the same set of load maxima is assumed to represent all vehicle passages considered. Repeated application of this procedure over several iterations yields the accumulated differential settlement and the associated evolution of support conditions, including the redistribution of loads between neighbouring sleepers [5, 16].

Table 1: Parameters of the 2D track and vehicle models.

Component	**Properties**
Rail	$\rho_\mathrm{r} = 7800$ kg/m^3, $EI = 6.4$ MN·m^2
Rail pad	$k_\mathrm{r} = 40$ MN/m, $c_\mathrm{r} = 5$ kN·s/m
Sleeper	$m_\mathrm{s} = 150$ kg
Support	$k_\mathrm{s} =$ spatially varying (example in Figure 4), $c_\mathrm{s} = 30$ kN·s/m
Vehicle body	$M_\mathrm{c} = 111 \times 10^3$ kg, $J_\mathrm{c} = 1.7 \times 10^6$ kg·m^2, $\Delta_\mathrm{c} = 10.3$ m
Bogie	$M_\mathrm{b} = 800$ kg, $J_\mathrm{b} = 730$ kg·m^2, $\Delta_\mathrm{b} = 6.77$ m
Wheelset	$M_\mathrm{w} = 1341$ kg, $J_\mathrm{w} = 100$ kg·m^2, $\Delta_\mathrm{w} = 1.78$ m
Primary suspension	$k_1 = 30$ MN/m, $c_1 = 70$ kN·s/m
Secondary suspension	$k_2 = 3.75$ MN/m, $c_2 = 10$ kN·s/m

ρ denotes density; EI rail bending stiffness; M mass; J mass moment of inertia; k stiffness; c damping coefficient; and Δ spacing. Subscripts r, s, c, b, and w denote the rail, support, car body, bogie, and wheelset, respectively.

2.2 Solution strategies for long-term settlement prediction

Long-term settlement is evaluated using two alternative solution strategies. In the non-iterative (constant load) approach, settlement is extrapolated over a prescribed number of load cycles while keeping the sleeper–ballast contact-force distribution fixed. In the iterative approach, the track model is updated at discrete intervals based on the accumulated settlement, allowing changes in support conditions and the resulting redistribution of loads to be captured. The computational procedures for both approaches are summarised in Figure 2. In this context, the term iterative refers to the updating of track geometry and support conditions and is independent of whether the underlying support model is linear or non-linear, see Figure 3.

Non-linear behaviour may additionally be introduced through state-dependent material properties or non-linear contact conditions at the sleeper–ballast interface, including loss of contact due to voided sleepers (DIFF). The simulations presented therefore quantify the influence of modelling assumptions on predicted long-term differential settlement under spatially varying support conditions.

2.3 Empirical settlement models

The empirical settlement models are used to relate the simulated sleeper–ballast contact forces to permanent (inelastic) deformation of the ballast. Two formulations are employed in this study: the model proposed by Varandas et al. [12], implemented in ROSE, and the model proposed by Nasrollahi et al. [5], implemented in DIFF.

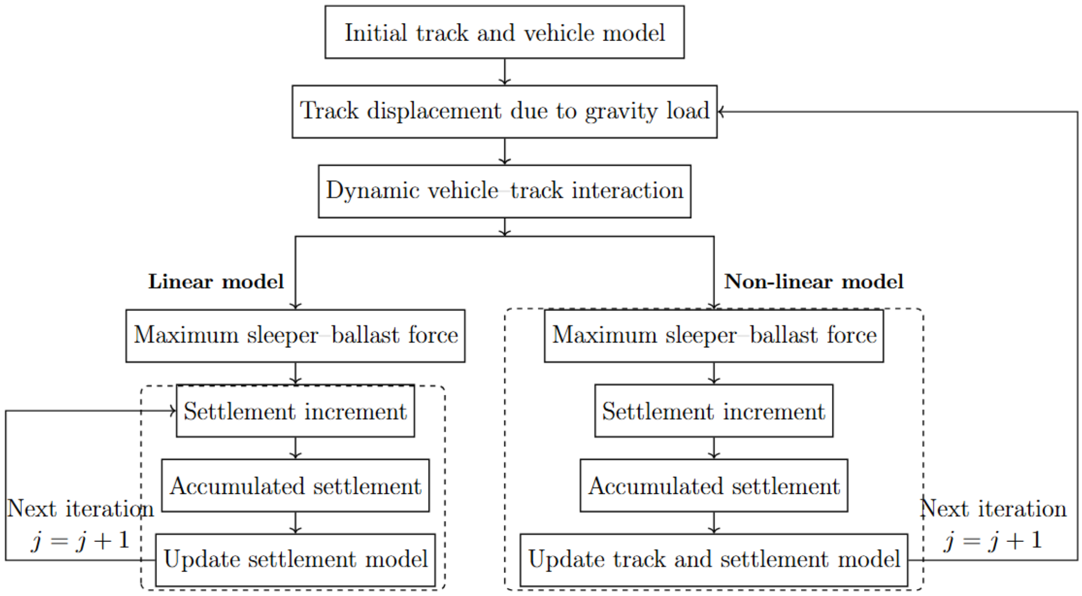


Figure 2: Procedure for predicting differential settlement in an open ballasted track using non-iterative or iterative solution strategies.

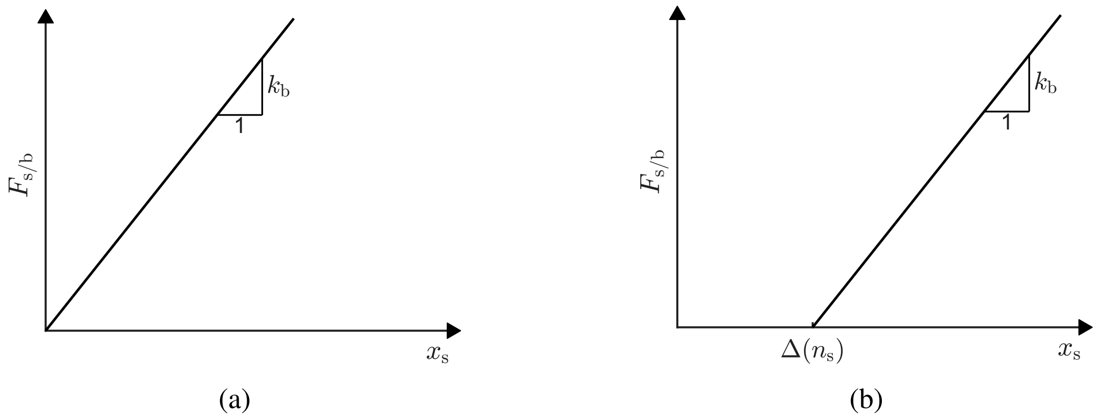


Figure 3: Principle illustration of alternative force–displacement characteristics for the ballast/subgrade support: (a) linear and (b) piecewise-linear behaviour. Here, x_s denotes the downward sleeper displacement, $F_{s/b}$ the sleeper–ballast contact force, and k_b the support stiffness. In the piecewise-linear model, a potential gap $\Delta(n_s)$ is introduced, representing a local loss of sleeper–ballast contact. The support force develops only after the sleeper displacement exceeds $\Delta(n_s)$, where n_s is the iteration number.

The model by Varandas et al. uses the history of sleeper–ballast contact force to compute the incremental permanent (inelastic) ballast deformation. For each sleeper i, the maximum contact force during each loading cycle, $\max(F_{s/b,i})$, is extracted and used to evaluate the settlement increment. The formulation captures both the initial rapid compaction and the subsequent slower accumulation observed in tamped tracks [9]. The incremental settlement for sleeper i during loading cycle l is given by

$$\delta_{i,l} = \frac{\zeta}{M_{\alpha\beta}} \int_0^{F_{\text{s/b},i}} (F_{\text{s/b},i})^{\alpha} \left(\frac{1}{h(F_{\text{s/b},i}) + 1} \right)^{\beta} dF_{\text{s/b},i}. \tag{1}$$

The accumulated settlement after N_s loading cycles is then obtained by summation

$$\Delta_{i,l} = \sum_{l=1}^{N_\text{s}} \delta_{i,l}. \tag{2}$$

Here, α, β, and ζ are material parameters, while $h(F_{\text{s/b},i})$ is a load-history function updated after each loading cycle to account for the cumulative number of load exceedances. The normalisation term $M_{\alpha\beta}$ ensures that ζ represents the settlement produced by a reference load of $F_\text{ref} = 50$ kN applied over $N_\text{ref} = 10^6$ loading cycles.

In the DIFF framework, short-term vehicle–track dynamics are simulated in the time domain using the static gravity-loaded track configuration as the initial state. For the vehicle passage simulated in iteration step j ($j = 1, 2, \ldots, n_\text{s}$), the incremental settlement $\delta_{i,j}$ [m] at sleeper i ($i = 1, 2, \ldots, N_\text{bays} - 1$) is expressed as a function of the maximum of the sleeper–ballast contact force, max($F_{\text{s/b},i}$), generated during each wheel passage n:

$$\delta_{i,j} = \sum_{n=1}^{N_\text{w}} \left\{ \sum_{k=1}^{N_k} a_k \left[\frac{\max(F_{\text{s/b},i})_n - F_{\text{th},i}}{F_0} \right]^{\beta_k} \right\}, \tag{3}$$

and the accumulated settlement for each sleeper after n_s iteration steps is

$$\Delta_{i,j} = \sum_{j=1}^{n_\text{s}} \delta_{i,j}. \tag{4}$$

where N_w is the number of wheels (here N_w = 4), N_k, a_k, and β_k are empirical model parameters, and $F_0 = 1$ kN is a reference force. Permanent displacement accumulates only when the maximum contact force exceeds the threshold $F_{\text{th},i}$, as enforced through the Macaulay brackets. The threshold force evolves with the accumulated settlement according to

$$F_{\text{th},i}(\Delta_{i,j}) = F_{\text{th},\infty} - \big(F_{\text{th},\infty} - F_{\text{th},0}\big) e^{-\gamma \cdot \Delta_{i,j}}, \tag{5}$$

where $F_{\text{th},0}$ and $F_{\text{th},\infty}$ denote the initial and long-term threshold values, respectively, and γ controls the hardening rate. In the non-iterative approach, the threshold is updated every 10^3 loading cycles based on the accumulated settlement.

The empirical settlement models are applied within both non-iterative and iterative solution strategies. In the non-iterative approach, the same load distribution is used for all cycles, whereas in the iterative approach, the load magnitudes are updated based on the evolving track configuration, leading to a history-dependent evolution of settlement.

3 Comparison of modelling frameworks and solution strategies

A long-term analysis based on Track Recording Car (TRC) measurements of longitudinal level collected between 1997 and 2016, together with occasional measurements of track stiffness, has previously been reported for two sections of the Swedish heavy-haul line Malmbanan [14, 16]. For the 3 km section considered in this study, the mean support (Winkler-type) stiffness per rail side was found to be 35.5 (kN/mm)/m, corresponding to an equivalent mean sleeper support stiffness of 110 kN/mm. The standard deviation was 15.4 (kN/mm)/m, yielding a coefficient of variation of 0.43.

Based on these statistics, samples of sleeper support stiffness were generated as spatially correlated random fields following the methodology of Vanmarcke [17], assuming a lognormal distribution and an exponential correlation function. The fields are characterised by the prescribed mean, coefficient of variation, and correlation length [14]. From this ensemble, a single representative realisation was selected for further analysis. The spatial distribution of sleeper support stiffness for the selected realisation is shown in Figure 4. This realisation is used to compare the response obtained using non-iterative and iterative solution strategies within the ROSE and DIFF frameworks.

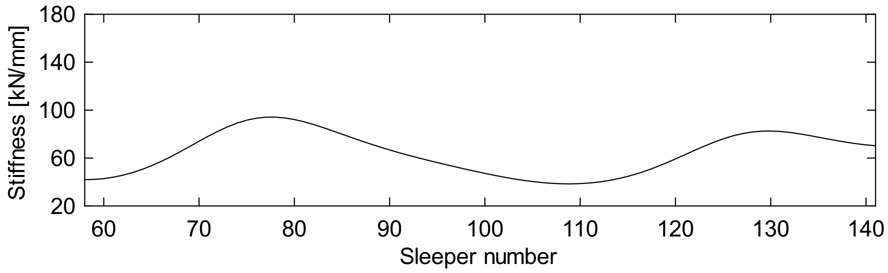


Figure 4: A realisation of sleeper support stiffness along 50 m of the (centre part of the) track model. Correlation length 10 m and coefficient of variation 0.43.

3.1 Track receptance and short-term responses

A vertical harmonic load in the frequency range 0–500 Hz was applied on the rail above sleeper 101 (to minimise boundary effects from the far rail ends on the dynamic response) in order to evaluate the dynamic characteristics of the track. The point receptance, defined as the ratio of displacement to applied force, obtained from the ROSE and DIFF models is compared in Figure 5. The results show good agreement between the two frameworks, indicating that they reproduce similar dynamic behaviour over the considered frequency range.

Two resonance frequencies and one anti-resonance frequency can be identified within the investigated frequency interval. The first resonance frequency, at approximately 62 Hz, is associated with the in-phase motion of the rail and sleepers, whereas the second, at around 320 Hz, corresponds to out-of-phase motion between the rail and sleepers.

A comparison of the short-term dynamic responses obtained from the ROSE and DIFF frameworks was carried out by examining the vertical rail displacement and the sleeper–ballast contact force. The predicted time history of the vertical rail displacement above sleeper 101 at the centre of the track is presented in Figure 6 (left), while the corresponding sleeper–ballast contact force at the same location is shown in Figure 6 (right). The results demonstrate that the two models produce very similar response histories in terms of both amplitude and shape. The peak rail displacement reaches approximately 2 mm, while the maximum sleeper–ballast contact force is about 55 kN. Overall, the agreement between the ROSE and DIFF frameworks is good. The close agreement in short-term dynamic response provides confidence in the consistency of the two frameworks for subsequent long-term settlement analysis.

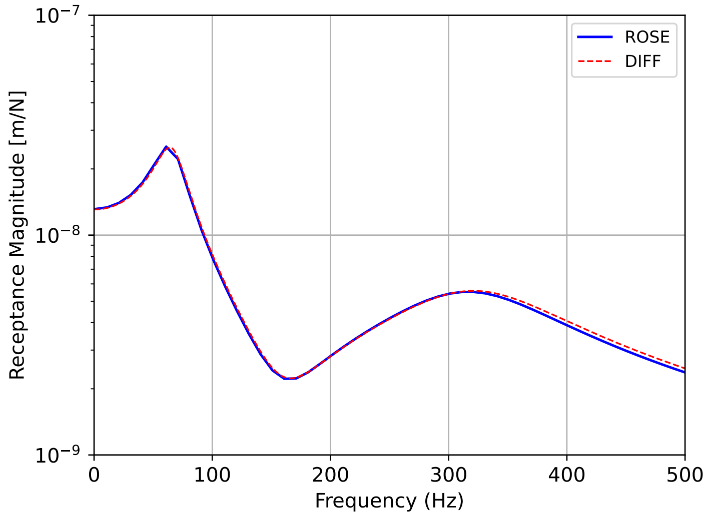


Figure 5: Magnitude of the vertical direct rail receptance calculated using the ROSE and DIFF frameworks at the centre of the track model.

3.2 Long-term settlement behaviour

To evaluate the influence of iterative model updating on long-term settlement predictions, the non-iterative and iterative approaches described in Section 2 are compared using the same realisation of the sleeper support stiffness, shown in Figure 4. In the non-iterative approach, a constant distribution of sleeper–ballast contact forces is assumed throughout the analysis, whereas in the iterative approach, the track model is updated as settlement accumulates.

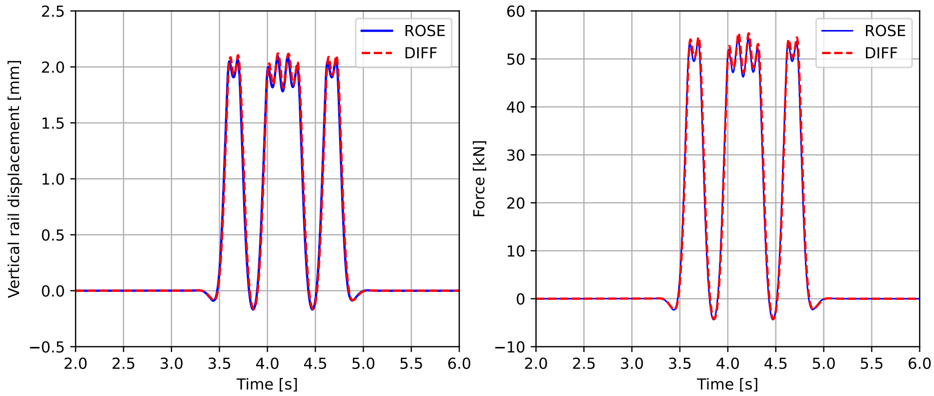


Figure 6: Comparison of short-term responses obtained from the ROSE and DIFF frameworks: time histories of the vertical rail displacement above a sleeper at the centre of the track (left), and the corresponding sleeper–ballast contact force (right).

The calibrated parameter values adopted for both settlement models are taken from [14]. For the model of Varandas et al. [12], $\alpha = 0.6$, $\beta = 0.82$, and $\zeta = 10$ mm. For the model of Nasrollahi et al. [11], $a_1 = 0.0002$ mm/1000 cycles, $\beta_1 = 2.0$, $F_{\text{th},0} = 30$ kN, $F_{\text{th},\infty} = 80$ kN, and $\gamma = 0.12\ \text{mm}^{-1}$.

In the iterative approach implemented in DIFF, the track model was updated whenever the settlement increment computed for any sleeper reached 0.2 mm, or when the accumulated tonnage within a given iteration step reached 1.2 MGT (10^4 load cycles with loaded wagons). The calibrated parameter value β_1 = 2.0 in the empirical settlement model leads to a rapid evolution of settlement during the initial load cycles, representing the early phase of track settlement. Consequently, the number of load cycles included in the initial iteration steps must be kept very small to prevent the settlement increment from exceeding the 0.2 mm threshold. As a result, the total simulation time for the iterative DIFF analysis was on the order of 48 hours, requiring 47 iterations with successive updates of the track model. By contrast, the corresponding simulation using the non-iterative approach required approximately 5 minutes, as the track model and load response remain fixed throughout the analysis. In the ROSE framework, the iterative approach required approximately 90 minutes and a total of 75 iterations, while the non-iterative simulation took about 5 minutes.

The spatial settlement profiles after 365 days obtained from DIFF and ROSE using the non-iterative and iterative approaches are compared in Figures 7(a,b) and 8(a,b), respectively. The relative difference in accumulated settlement, shown in Figures 7(c) and 8(c), was quantified as the percentage deviation between the predictions of the two approaches. For each sleeper, the deviation was evaluated relative to the settlement predicted by the non-iterative approach, thereby providing a measure of the extent to which the iterative prediction exceeded or underestimated the corresponding non-iterative prediction. The results indicate that both formulations produce essentially the same spatial settlement pattern, which is primarily governed by the prescribed variation in sleeper support stiffness. Higher sleeper–ballast contact forces, and consequently larger settlements, are consistently observed in track sections with higher support stiffness.

The differences between the two approaches are small at early stages and increase only moderately as settlement accumulates. For the stiffness profile shown in Figure 4, corresponding to a correlation length of 10 m, the relative deviations are typically within a few percent after $t = 25$ days (not shown) and remain below approximately 4% after $t = 365$ days. For a second stiffness realisation with a shorter correlation length of 5 m, the relative deviations increase to about 10% after $t = 365$ days.

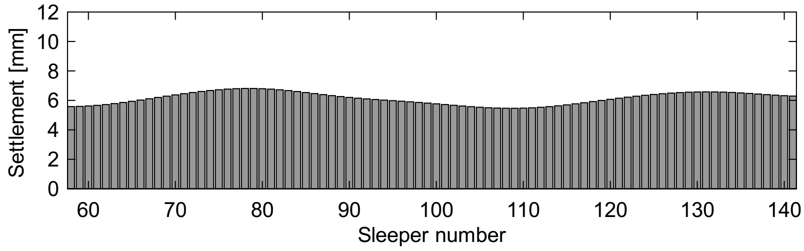
These results indicate that the non-iterative approach provides a reasonable prediction of accumulated settlement in open track, provided that there is no pronounced tendency for the development of voided sleepers leading to substantial load redistribution between adjacent sleepers. Such effects may become important in more complex situations, for example in transition zones [11] or at rail joints with dipped welds [16], where localised changes in support conditions can strongly influence the load distribution.

To further illustrate the settlement evolution, the settlement history at sleeper 72 is shown in Figure 9(a,b). As observed in the spatial settlement profiles, the ROSE framework predicts substantially larger settlements than the DIFF framework throughout the simulation. The non-iterative and iterative approaches predict very similar settlement growth throughout the simulation period. In the DIFF framework, the iterative approach results in slightly larger settlements than the non-iterative approach, whereas the opposite trend is observed in the ROSE framework. Nevertheless, the differences remains limited to a few tenths of a millimetre after approximately 5×10^5 load cycles. These small deviations arise from the iterative updating of the track geometry and the resulting evolution of support conditions. As settlement accumulates, changes in sleeper support lead to a redistribution of sleeper–ballast contact forces between neighbouring sleepers. In the ROSE framework, this redistribution results in a steeper initial settlement rate followed by a more gradual increase during the later stages of the simulation. However, for the open ballasted track considered here, these redistribution effects have only a minor influence on the accumulated settlement, leading to close agreement between the non-iterative and iterative approaches.

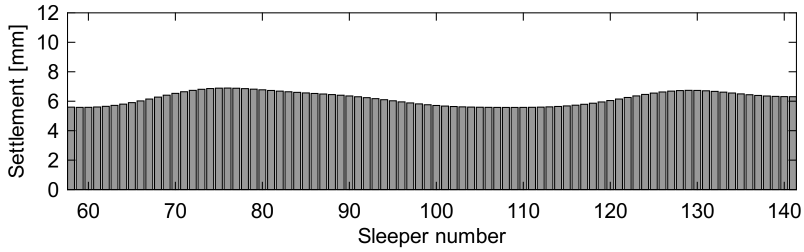
4 Conclusions

A comparison between non-iterative and iterative approaches for predicting long-term differential settlement in ballasted railway tracks has been presented. The ROSE and DIFF modelling frameworks were shown to provide consistent predictions of both the dynamic track response and the long-term settlement behaviour, thereby supporting the validity of the adopted modelling approach.

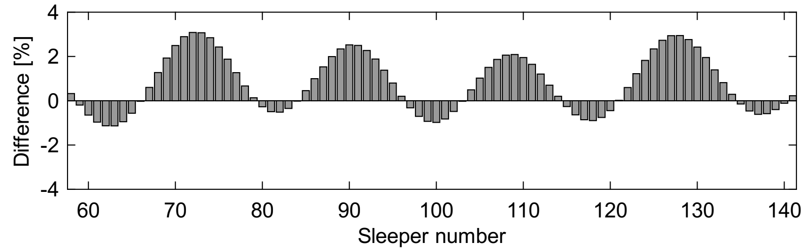
The results demonstrate that the spatial distribution of settlement is primarily gov-



(a)



(b)

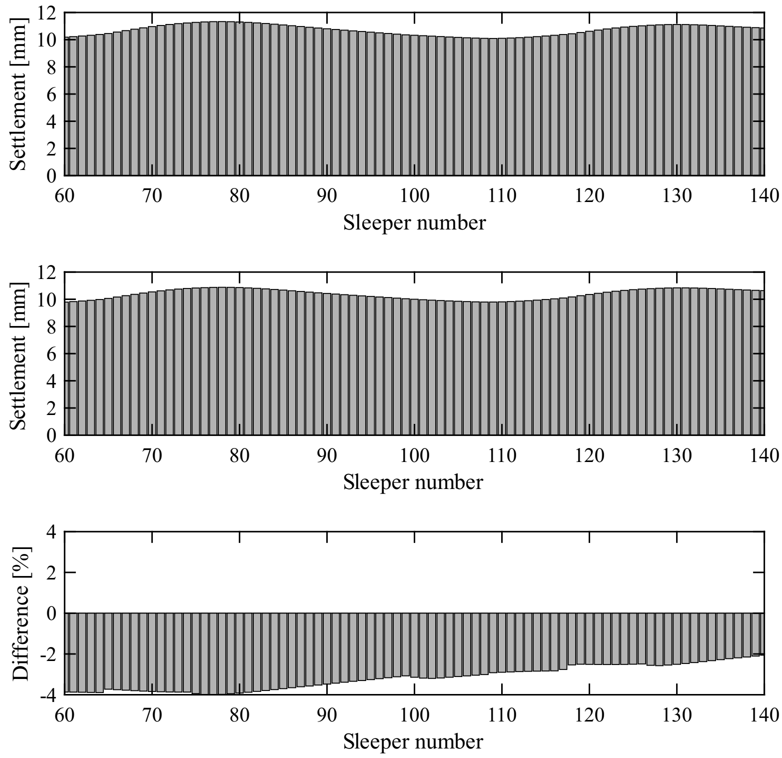


(c)

Figure 7: Comparison of predicted long-term settlement after 365 days (15 MGT) along a 50 m track segment using non-iterative and iterative modelling approaches, based on the sleeper support stiffness realisation shown in Figure 4 with a correlation length of 10 m [14]: (a) Non-iterative model; (b) Iterative approach with a settlement threshold of 0.2 mm per iteration; (c) Relative difference between the non-iterative and iterative model predictions. Results were obtained using the DIFF simulation framework.

erned by variations in sleeper support stiffness, which control the magnitude of sleeper–ballast contact forces. Although the iterative approach accounts for the evolution of track geometry and the associated redistribution of loads between sleepers, these effects were found to have only a limited influence on the accumulated settlement for the open track conditions considered. As a result, both approaches yield very similar settlement patterns and comparable magnitudes of long-term settlement.

From a practical perspective, the findings indicate that the non-iterative approach provides an efficient and sufficiently accurate approximation for predicting long-term settlement in open ballasted track, with substantial reductions in computational cost.



(c)

Figure 8: Comparison of predicted long-term settlement after 365 days (15 MGT) along a 50 m track segment using non-iterative and iterative modelling approaches, based on the sleeper support stiffness realisation shown in Figure 4 with a correlation length of 10 m: (a) Non-iterative model; (b) Iterative approach with a settlement threshold of 0.15 mm per iteration; (c) Relative difference between the non-iterative and iterative model predictions. Results were obtained using the ROSE simulation framework.

In contrast, the iterative approach offers additional insight into the coupled evolution of track geometry, support conditions, and load redistribution, and is therefore more appropriate in situations where these effects are expected to be significant, such as in transition zones or in the presence of voided sleepers.

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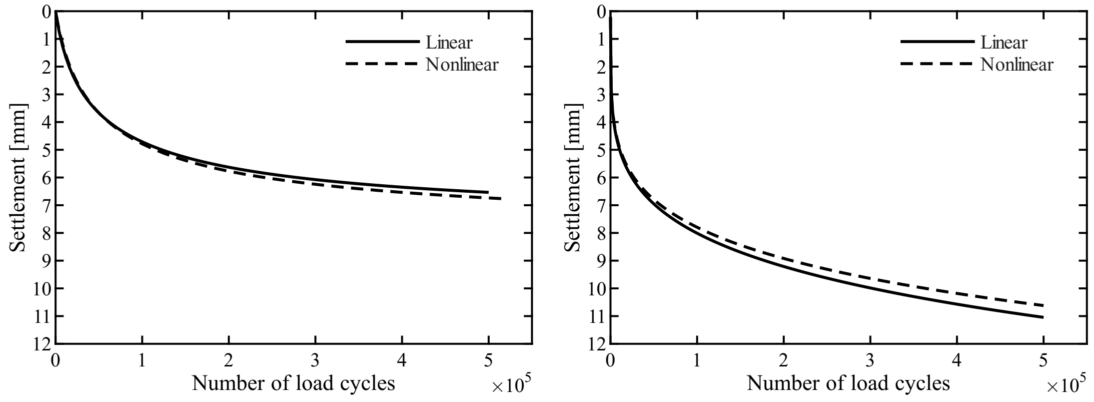

(a) (b)

Figure 9: Evolution of long-term settlement over one year of traffic (15 MGT), as predicted by the (a) DIFF and (b) ROSE frameworks, based on a single realisation of sleeper support stiffness (see Figure 4) with a correlation length of 10 m.

European Union nor the granting authority can be held responsible for them.

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