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Assessment of an iterative settlement procedure in railway switches and crossings using two different approaches

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Abstract. Differential settlement in transition zones of railways tracks is a consequence of variable track stiffness and load distribution potentially leading to the development of voided sleepers. This paper addresses the simulation of differential settlement in transition zones of turnouts. An iterative settlement procedure (ISP) has recently been proposed which combines short-term simulations of the vehicle-track interaction with long-term assessments of the settlement. A finite element model is used in order to estimate the track sublayers stresses. Owing to the asymmetry of turnouts, this ISP is extended in order to consider non-symmetry. The symmetrical and non-symmetrical approaches are compared in the case study of the Shift2Rail demonstrator located near Vienna, Austria. The transition zone between the plain line and the switch panel is considered where a good calibration of the short-term model is obtained. Further works should study the influence of flexible sleepers, the level of discretization and the dynamic contribution of substructure stresses. The novel non-symmetrical approach should prove even more relevant in the transition zone between long and short bearers in the crossing panel. Long-term monitoring tests on the track settlement are recommended to verify the accuracy of the proposed settlement prediction model. It is hoped that the novel approach can be used to help design and/or validate innovative concepts of turnouts and their effects on train dynamics.

Keywords: Track settlement, Vehicle-track interaction, Switches and crossings, Transition zone, Comparison tests / simulations

1 Introduction

Railway transition zones (TZ) exhibit variable stiffness characteristics leading to large variation in vehicle-track dynamics and hence differential track settlement, potentially leading to voided sleepers. Assessment of the differential settlement may be addressed via an iterative settlement procedure (ISP) coupling short-term dynamic simulations

and long-term assessments of the settlement [1]. A coupled procedure is required as loads applied by the rolling stock on the one hand, and differential settlement on the other hand have a mutual influence on each other. This paper focuses on the TZ between the plain line (PL) and the switch panel of a turnout.

From top to bottom, a PL track is composed of the superstructure: rails, rail pads, sleepers and possibly under sleeper pads (USP). A ballasted substructure is composed of the ballast, the sub-ballast, the subgrade, the embankment. In switches and crossings (S&C), the substructure is usually uniform, while the superstructure is asymmetrical and varies along the track. The stiffness variation consists in varying properties of the track superstructure componentry such as rail profiles, rail pads and baseplate pads, length of sleepers, USP...

Two different approaches for the computation of the settlement are compared. The former one assumes a left/right symmetrical long-term response of the track, as it is the case in the majority of the models. The latter approach, recently developed, considers asymmetry of applied loads and track structure.

The case study is the Shift2Rail demonstrator located near Vienna, Austria. In situ measurements allow a calibration of short-term simulations of the vehicle-track interaction (VTI) model. A good calibration is obtained by assuming a clearance between a part of the instrumented sleeper and the ballast. The symmetrical ISP and the novel non-symmetrical ISP are compared qualitatively in this case study, as settlement has not been measured.

2 Methodology

2.1 Iterative settlement procedure

The procedure is an extension of the one thoroughly described by Grosioni et al. [1]. The whole contact area where settlements are assessed is divided into N_c interfaces. In [1], only one interface per sleeper of longitudinal position x_i was possible, and half a model was considered owing to symmetry. Here in the non-symmetrical approach, a doublet (x_i, y_i) is assigned to each interface: the contact area under a sleeper is divided in an arbitrary number of interfaces along the lateral coordinate y . Moreover, the symmetrical VTI module used in [1] is replaced by a 3D multibody system (MBS) software.

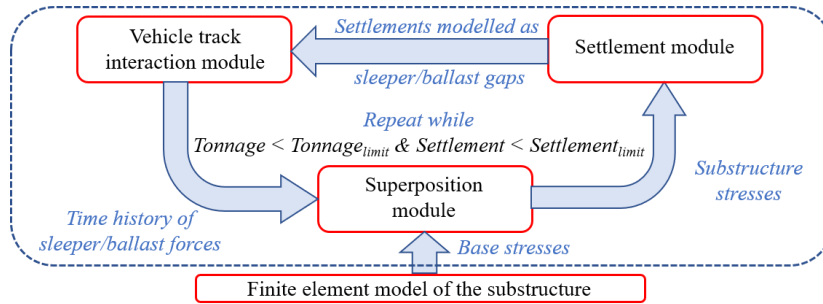


Fig. 1. Flowchart of the iterative settlement procedure (ISP)

A flowchart of the procedure is shown in **Fig. 1**. It starts with a VTI simulation of the initial track. Time histories of sleeper/ballast forces $F_j(t)$ are output from the VTI module to the superposition module where N_l contributions are summed in order to assess the stress state at a depth z_k below the i -th interface:

$$\bar{\sigma}_i(z_k, t) = \sum_{j=1}^{N_l} \bar{\sigma}_{1ij}(z_k) F_j(t), \quad (1)$$

where $F_j(t)$ is a multiplier of the static linear unit stresses $\bar{\sigma}_{1ij}(z_k)$ precomputed out of loop in a finite element (FE) model of the substructure. The number of interfaces considered for the loading N_l has to be greater than N_c in order to avoid edge effects. Stress tensors $\bar{\sigma}_i(z_k, t)$ are output to the settlement module where suitable empirical laws are used. Settlement values δ_i at each interface are finally fed back to the VTI module where they are considered as additional gaps in springs linking sleeper to ballast:

$$F_i = K_i \langle u_{zi} - \delta_i - g_i \rangle, \quad (2)$$

where K_i is the stiffness of the spring, u_{zi} is the vertical displacement of the sleeper at the i -th interface, g_i is the gap in the initial track model, and $\langle \cdot \rangle$ is the Macaulay bracket. The iterative procedure goes on till a limit is reached, either related to a maximal settlement value or to a tonnage value.

The robustness of the procedure relies on the assumption that the VTI simulation at a given iteration is representative of the load cycles concerned by this iteration. This may be controlled by the user through a criterion limiting the increment in differential settlement between 2 iterations. This criterion is set to 0.2 mm in the following.

The common approach assuming symmetry may be reproduced by applying to each sleeper the mean value of the interface forces along the lateral direction. In the following, details are provided on some of the modules involved in the ISP.

2.2 Vehicle track interaction

The MBS software VOCO [2] is used, some of its features being required for simulating vehicle dynamics in S&C:

1. The changing geometries of sections in wheel/rail (W/R) contact.
2. The changing contact on different rail bodies (e.g. stock and switch rail)
3. Lateral dynamics (especially in a diverging route)

The VTI procedure [3] consists in a co-simulation between vehicle and track dynamics, where, at each time step, W/R contact forces are applied to the track model, while structural rail displacements under each wheel are fed back to the vehicle model, where they are considered as an irregularity which is added to the track geometry.

In order to handle the complex geometry of turnouts, track dynamics may be handled by a third-party FE code [3], but this may significantly increase computing time when inserted in the iterative loop of **Fig. 1**. An internal flexible track model has been developed during the DYNOTRAIN project [4]. This module has been recently enhanced in order to address S&C:

1. Modelling of an *arbitrary* number of rails (stock rail, switch rail, check rail...) with beam elements
2. Modelling of an *arbitrary* number of rigid bodies (sleeper, baseplate, LP model representing the substructure [1]...)

2.3 Settlement module

The settlement module is a library of settlement laws for specific materials. Each settlement law is typically a function of applied stress and number of load cycles. In this study, settlement originating only in the ballast layer is calculated. To calculate settlement at the ballast-sleeper interface, each material layer is divided into sub-layers and plastic strain at each sub-layer's central-point is calculated based on the number of load cycles at the end of the iteration and the stress calculated from VTI sleeper loads. The plastic strains are integrated as follows:

$$\delta = \sum_{i=0}^n \varepsilon_{p,i,j} H_i, \quad (3)$$

to find δ , settlement at ballast-sleeper interface; where n is the total number of layers considered, $\varepsilon_{p,i,j}$ is the plastic strain resulting from the applied loads and calculated at the mid-point within the layer. H_i is the height of the i -th layer. Non-integer values of the load cycles are permitted and allow a more realistic settlement profile, especially in the early cycles.

3 Case study

3.1 Description

Shift2Rail demonstrator turnouts are installed near Vienna with standard and optimized designs [5]. The turnouts are instrumented with displacement and acceleration sensors, strain gauges and pressure sensors. The TZ between the PL and the switch panel of the optimized turnout # 4 is studied (**Fig. 2** left). At this TZ, displacement sensors (**Fig. 2** right) have been set on the steel hollow bearer with a point operating equipment (POE). Several running conditions have been tested with a SIEMENS ER20 locomotive:

- Trailing and facing direction
- Through and diverging route
- Various speeds (10, 60, 80, 120 km/h), the diverging route being only run at 60 km/h

As traffic occurs mainly in a facing through direction, this configuration at 120 km/h is selected for the long-term analysis. The turnout is located in a large curve, so that curving effects are present in a through route. Displacements (**Fig. 3**) on the inner (right) side are larger than in the outer (left) side, which may seem paradoxical. This occurs also at low speed (**Fig. 3** right) where curving effects are negligible. Hence the origin of the asymmetry is structural. As this behaviour may also be observed in a diverging route (not plotted here), it should not be related to a larger stiffness on the active side due to the switch rail being pressed against the stock rail.

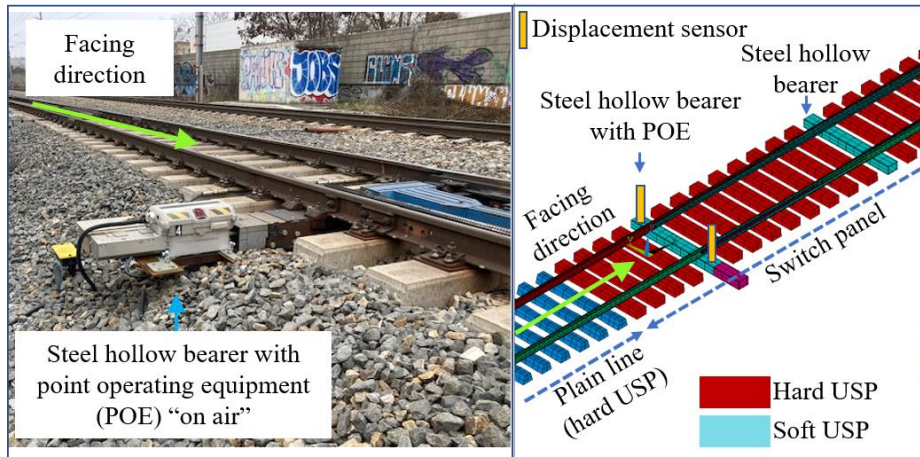


Fig. 2. Shift2Rail demonstrator: picture of turnout #4 (left), details of FE model of superstructure with location of displacement sensors of the instrumented sleeper with POE (right)

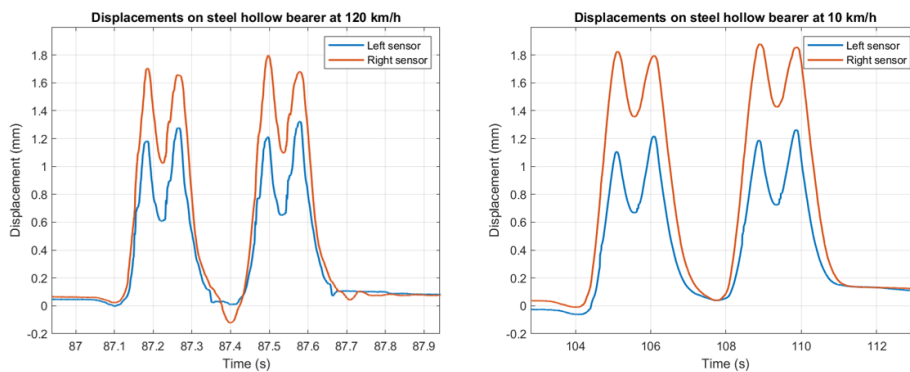


Fig. 3. Measures of displacements at left and right sensors of steel hollow bearer with POE in facing through direction at the passage of a locomotive at 120 km/h (left), 10 km/h (right)

3.2 Modelling

Vehicle dynamics. The vehicle is issued from a nonlinear model of a French loco BB26000 [7], modified with the SIEMENS ER20 axle load, bogie pivot spacing, bogie wheelbase and wheel radius [8]. The track layout is a curve of radius 3520 meters without cant. Switch and stock rail profiles are computed via a numerical tool reproducing the machining [6].

Flexible track. The FE model of the whole turnout (**Fig. 2** right) is used as a reference. The internal flexible track model only encompasses the PL and the first ten meters of the switch panel including the transfer zone between the stock rail and the switch rail.

The model is divided into 2 zones denoted A and B in **Fig. 4**. Zone A is a PL with rail pads. Zone B is an assembly of a baseplate rigidly linked to the stock rail and switch rail (although the switch rail may lift off in reality), and elastically linked to the sleeper through a baseplate pad.

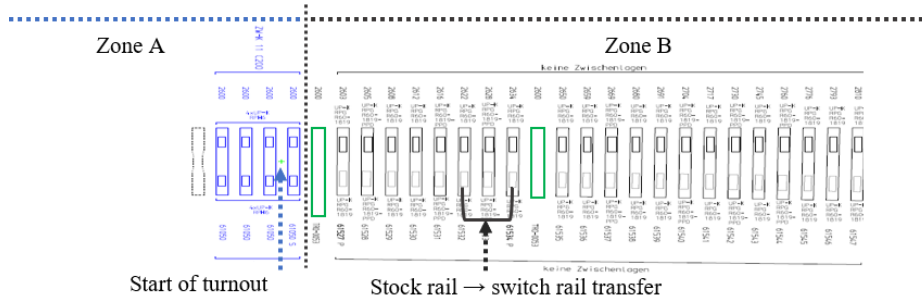


Fig. 4. Sketch of the transition zone

Stiff USP are set everywhere except below the steel hollow bearers pictured in green on **Fig. 4**, which are laid on soft USP. Rails are modelled with Timoshenko beams. Varying section properties in the switch rail are considered. Sleepers and baseplates are modelled with rigid masses. As sleeper displacements are asymmetrical (**Fig. 3**), the rotational degree of freedom of this body is active.

A sleeper/ballast interface is represented by 3 springs with gap, at the left, centre and right of the sleeper. The total stiffness between sleeper and ballast is the series stiffness of USP and track bed modulus. A reduction factor of 0.65 is applied to the USP stiffness [9]. The track bed modulus is unknown.

3.3 Calibration

A good calibration (**Fig. 5**) is obtained by setting the value of the track bed modulus to 0.1 N/mm^3 and by assuming a non-symmetrical support below the steel bearer caused by differential settlement. The larger displacement on the right side may be explained by a gap of 2.5 mm on the right side between sleeper and ballast and a stiffer ballast on the centre and left of the sleeper than elsewhere. The long-term analysis considered in the following section is carried out assuming a uniform support of the sleeper.

4 Long-term analysis

4.1 Settings

The FE model used for the computation of substructure stresses is shown on **Fig. 6**. Each coloured patch represents an interface associated to a spring in the VTI model (3 per sleeper). Settlement is computed at the 25 sleepers delimited by the red arrow. Outside this zone, settlement values are extrapolated when reinjected in the VTI model.

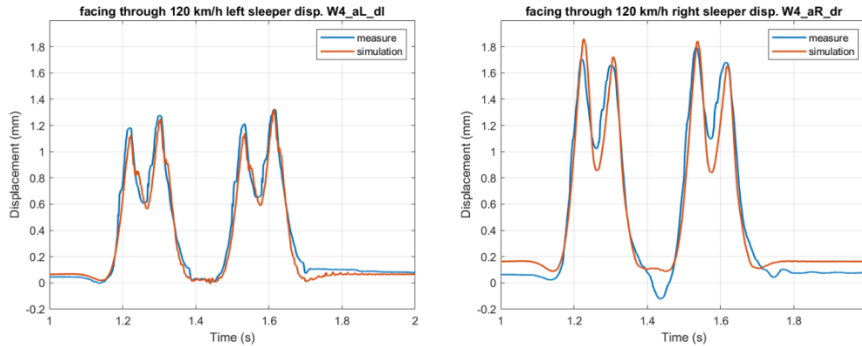


Fig. 5. Comparison measure/simulation of displacements at left and right sensors of steel bearer with POE in a facing through direction at 120 km/h

External loads are considered in the zone delimited by the orange arrow in order to avoid side effects in the computation of stresses in the red zone in expression 1. The substructure is composed of 3 materials: ballast, sub-ballast, subgrade. Sayed's settlement law is used for the ballast [12]. The procedure terminates after 1.1 million load cycles (axle passages) equivalent to 22 MGT.

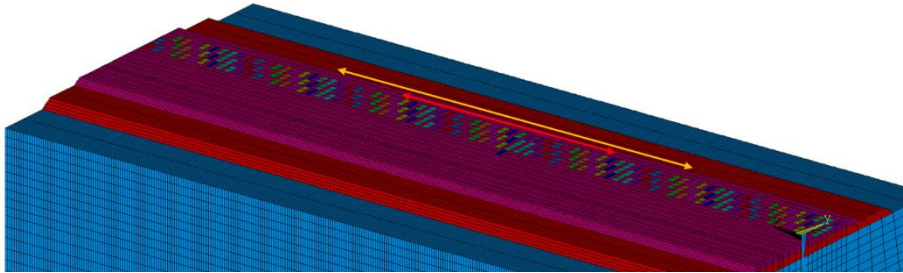


Fig. 6. Finite element model of the substructure

4.2 Comparison between symmetrical and non-symmetrical approaches

The procedure takes about 15 hours, and requires about 30 iterations.

Symmetrical approach. The differential settlement at the sleeper end level is shown on **Fig. 7**. For the sake of readability, results are not plotted at each iteration. Bumps correspond to soft USP at hollow bearers and are more pronounced as the number of cycles increases, because of the coupling between VTI and settlement.

Non-symmetrical approach. The evolution of settlement is plotted on both sides of bearers in **Fig. 8** and may be compared with the symmetrical approach of **Fig. 7**. As in the symmetrical approach, the two peaks correspond to the hollow bearers. Non-symmetrical results exhibit two main differences between left and right.

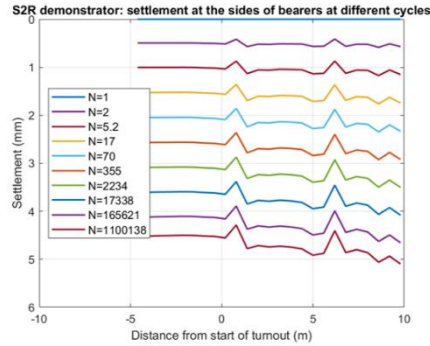


Fig. 7. Symmetrical approach. Settlement along the track at the sleeper end level

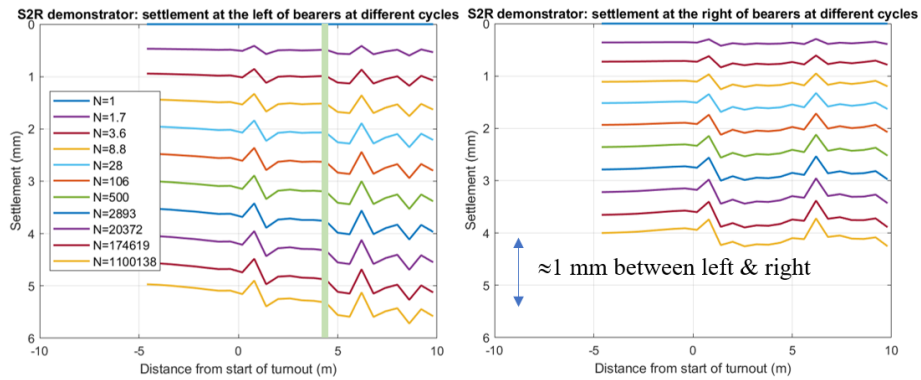


Fig. 8. Non-symmetrical approach. Evolution of settlement on both sides of bearers

First, the settlement is about 1 mm deeper on the outer side than in the inner side because of curving. Although by itself this difference is negligible, asymmetrical settlement might promote local defects of track geometry (e.g. twist/cross-level) given all other non-linearities at installation. Second, the effect of dynamics on settlement is more visible on the left side where rail profiles vary, noticeably after the transfer between the stock and switch rails, indicated by the vertical pale green line on the left of **Fig. 8**.

Results at the steel hollow bearer. On the left side of **Fig. 9**, settlement is plotted as a function of load cycles at the bearer with a POE with the symmetric approach. It may be checked that the settlement increment between 2 iterations is about 0.2 mm with more iterations at the first cycles in order to fit with the settlement law. The settlement at the centre is smaller, although applied loads are uniform by construction. This is due to the deviatoric stresses being smaller at the centre [10]. As a result, ballast/sleeper forces at the centre will be higher (expression 2). This result contradicts some measures [11] showing that pressures at the centre are smaller than below rail seats. Further works may be necessary as discussed in the conclusion.

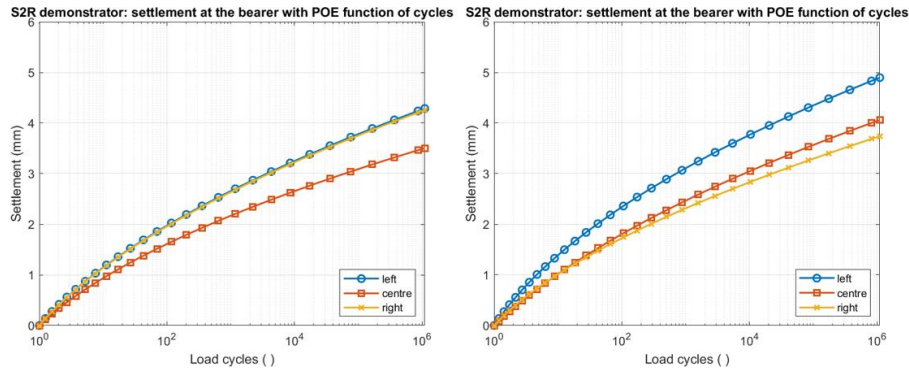


Fig. 9. Evolution of settlement at the left, centre and right of the steel hollow bearer with the symmetrical (left) and non-symmetrical (right) approaches

As shown on the right side of **Fig. 9**, the non-symmetrical approach shows its ability in predicting a variation of the settlement value along the length of the sleeper, and potentially the development of partially voided sleepers. As a perspective for future works, the non-symmetrical approach may prove to be even more relevant in the TZ between long and short bearers in the crossing panel.

5 Conclusion

An ISP has been proposed and tested in the case study of the Shift2rail demonstrator turnout. This is an extension of a procedure developed in the frame of the In2Track2 project [1]. The novel ISP may address non-symmetrical structures such as turnouts. It allows an insight into the asymmetrical dynamic behaviour. Main modifications are: 1) the insertion of a 3D VTI module instead of a 2D module, 2) the possibility to divide the sleeper/ballast area in as many interfaces as necessary along the lateral direction.

A good calibration of the VTI model with respect to measures has been obtained in the TZ between the PL and the switch. Comparison of symmetrical and non-symmetrical ISP has shown significant but not decisive differences between both approaches. Further works should address the TZ between long and short bearers at the crossing panel where measures are also available. At this TZ, the choice of a non-symmetrical ISP should be even more relevant.

Further improvements should consider flexible sleepers in the VTI model. The input in the superposition module of dynamic stresses instead of static ones is also under way. The level of discretization along a sleeper should also be investigated, and specifically its effect on the distribution of differential settlement and potentially voids.

Finally, there is a need in switches and crossings for long-term monitoring tests on the track settlement in order to verify the accuracy of the proposed settlement prediction model.

It is hoped that the adopted settlement procedure can be used to help design and/or validate innovative concepts of railway track switches and crossings and their effects

on train dynamics; and help track maintenance schedule and corrective actions caused by track settlement.

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