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Ballast settlement at transition zones: modelling via a non-linear lattice

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Abstract

This short paper presents, in a summarized way, non-linear connections for a lattice model of a railway, with the intention of simulating ballast compaction at transition zones.

Keywords: track degradation, railway transitions, ballast, lattice models.

1 Introduction

It is well established in the literature that zones where railway tracks exhibit changes in cross-sectional properties in the longitudinal direction are subject to increased track deterioration, which in turn leads to more frequent maintenance operations [1,2]. Such changes can take the form of stiffness variations in the foundation (for example, when the track passes over a rigid structure, like a culvert), transitions in track type (e.g., from ballasted to ballastless (slab) tracks), or even transitions from open track to civil structures (like bridges and tunnels). There is no complete physical understanding as yet of the accelerated degradation, but some causes are pointed out by different researchers [3–6]: i) the longitudinal variation leads to a dynamic response of the vehicle, which results in amplification of the train-track forces and therefore faster degradation; ii) due to the increased vehicle-track forces, soil and ballast settle faster at these regions, leading to an unlevelled rail profile and further amplifications; iii) due to presence of structures, the autonomous settlement of the foundation (soil consolidation, for example) may differ between the open track and the part of with the structure, which adds to the feed-back loop described in ii).

Indicators of track degradation are the increasingly unlevelled vertical position of the track, the occurrence of hanging sleepers, damage to the sleepers, ballast crushing, and others [3]. In order to design efficient mitigation solutions to this problem, it is important to understand the primary causes driving the deterioration of the track. Within this framework, the present work focuses on understanding if the compaction of ballast can be responsible, as a stand-alone mechanism, for cases of progressive loss of vertical geometry of an initially straight track.

The goals of the present work are to define a non-linear lattice representing the ballast layer, and to use it to assess the settlement behaviour of ballast in track transition zones. The non-linear lattice is defined such that its properties are tuned against lab tests of ballast layers under cyclic vertical loading [7]. The model that results from this work is versatile, can consider different types of trains, moving speeds, longitudinal changes and transitions at the foundation, and different ballast properties (tuned to lab experiments). The model can be used to assess how the vertical geometry of the track changes after each train passage, whether that process converges or not, how the train-track interaction force changes throughout time, and if hanging sleepers may occur or not.

2 Methods

The main framework for the model is based on the previous works by the authors [8,9] and will not be discussed here. Instead focus is put on the definition of the non-linear connections of the lattice, such that overall the compaction behaviour of ballast is replicated.

There are four main features of compacting ballast that the non-linear connection must take into account. These are: i) the successive increment of vertical displacement; ii) the load dependent settlement, i.e., the maximum settlement depends on the maximum load amplitude [10,11]; iii) the increase of the vertical stiffness [7,12]; iv) the inability to transmit tensile forces (which is a general property of unbound granular material). With these features in mind, the axial connections of the lattice are defined as depicted in Figure 1a, which represent a parallel assemblage of a linear spring (1), a stick-slip spring (2), and a spring with a gap (3). The load-unload cycle of this connection is as depicted in Figure 1b, which is similar to the load-unload cycles reported in cyclic loading of ballast (red line).

In order to allow accumulation of plastic displacement with the number of load cycles, the limit forces $F_{2,\max}$ and $F_{2,\min}$ must be reduced every time the force in the mid-connection exceeds $F_{2,\max}$. The amount this force reduces must be defined such that the compaction vs cycle number curve approximates that of lab tests. Due to limit of space, it is not explained here how such is done; for more details on that, reference is made to [13].

The diagonal and the shear connections of the lattice are also made non-linear, in order to simulate the frictional and the apparent cohesive behaviour of ballast. This is achieved by making the shear connection a stick-slip spring, whose sliding force depends on the force carried by the axial connection (F in Figure 1a), and by making the diagonal connection also a stick-slip spring, whose sliding force depends on the apparent cohesion. The way to define values for all the parameters of the 3 non-linear connections is explained in [13].

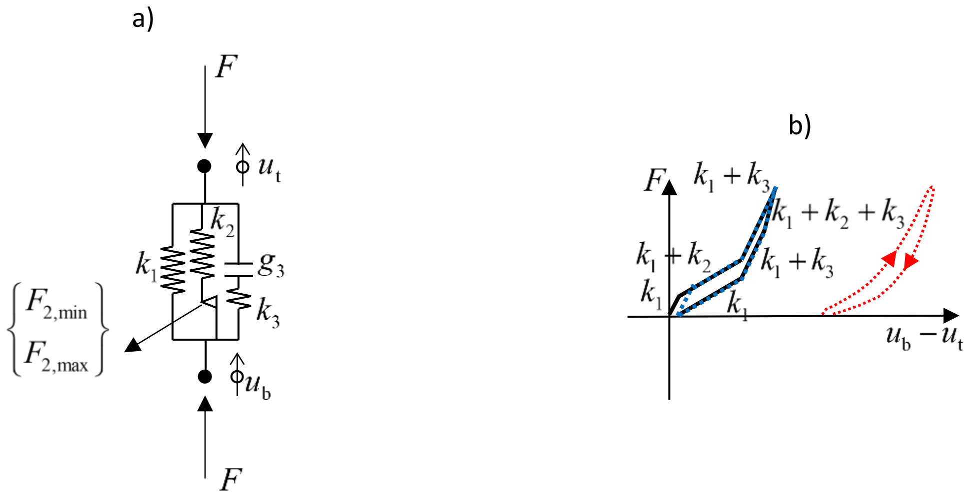

Figure 1: a) Axial connection aiming at reproducing the compaction behaviour of ballast. b) First (black) and second (dotted blue) load/unload cycles of the proposed connection, and sketch (dotted red) of a generic load-unload cycle of cyclic compaction tests.

3 Results

The non-linear model was applied to two railway transitions, one in the form of a transition from ballast track to slab track, and the other in the form of a culvert (and approach slabs) passing underneath a track. Several train passages excite these two transitions, and the position of the rail, ballast surface, and sleepers at the end of each passage is calculated. Figures 2-3 show the results after some passages. [Note: in order to speed up the process, the degradation factor (β_i in reference [13]) associated to the axial connection was increased; in this way, each train passage corresponds to multiple train passages; there was no further increased of plastic deformation after 20 passages – we stress that the number of passages is low because the degradation factor is artificially made too high.]

Figures 2a and 3a show that there is no differential settlement occurring case there is no transition. That is not surprising, since the train-track forces should remain constant, meaning that each sleeper will transmit the same force to ballast, and therefore the ballast settlement should remain the same everywhere.

For the case of the ballast-slab transition, it is seen that in the converged configuration, there is a differential position of the rail of about 2.5 mm spread over a few meters (Figure 2b). This is caused by the fact that one part of the track can settle (ballast) while the other cannot (slab). This differential position of the rail is associated with a rapid differential settlement of ballast and hanging sleepers (Figure 3b); a void of about 1 mm is obtained at the interface between ballast and slab.

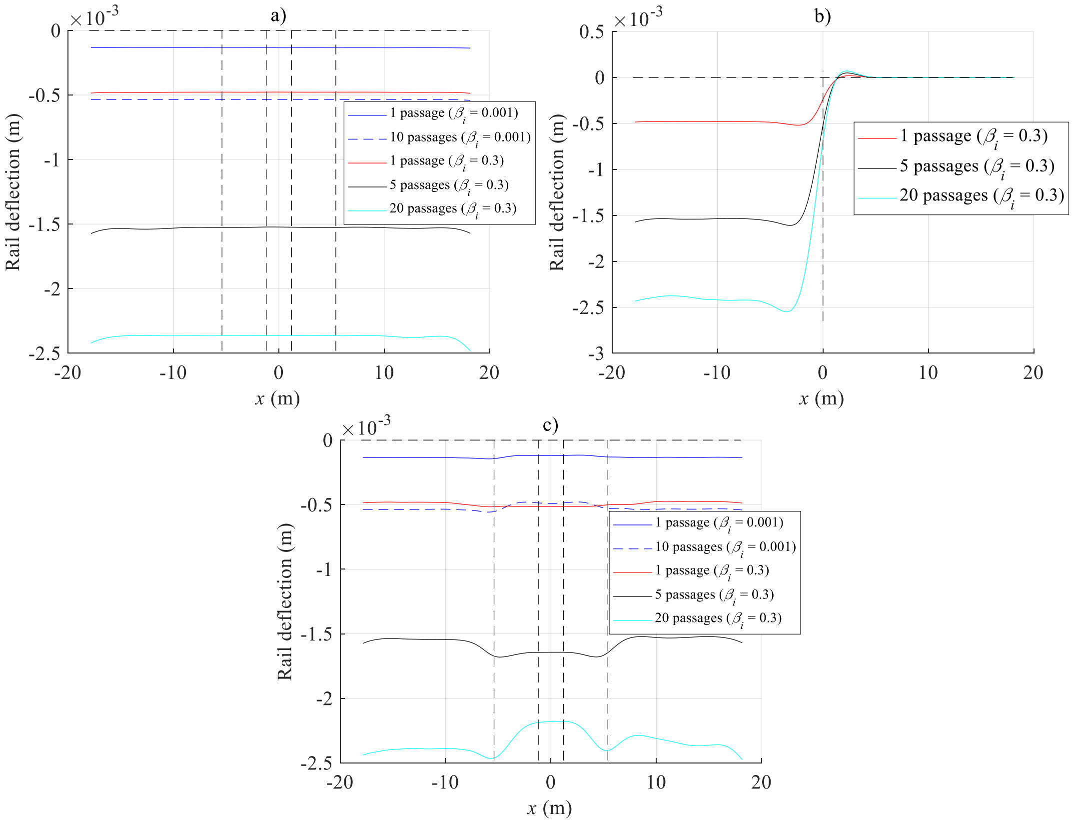

Figure 2. Rail position after train passages. a) no transition; b) ballast-slab transition; c) culvert with approach slabs.

For the case of the culvert, it is seen that the differential position of the rail is much smaller (less than 0.5 mm) and no hanging sleeper occurs. This is so because the load amplification at the transition is not large enough to cause large differential settlements of the ballast.

In all three scenarios, a converged situation has been reached. The initial expectation was that as differential settlements would occur, the track-train interaction forces would increase, and that would lead to even larger settlements, but that was not the case (results regarding train-track interaction force are not shown due to space limitation).

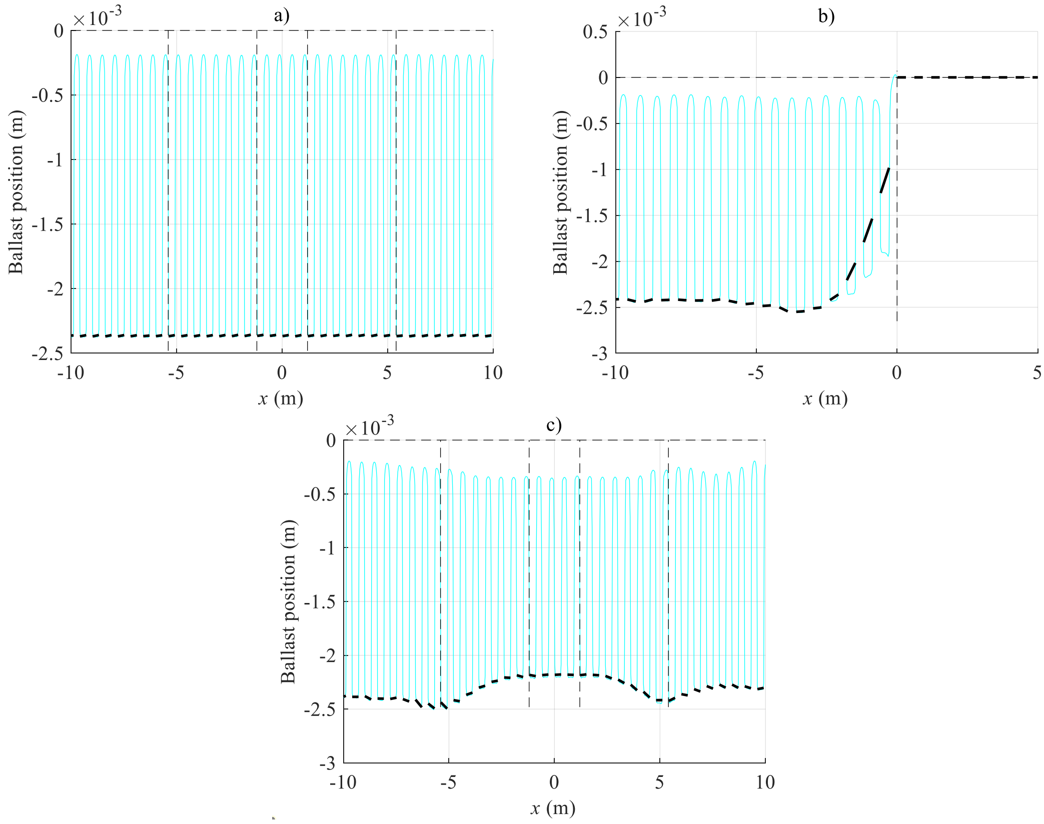

Figure 3. Position of ballast (cyan) and sleepers (black) after 20 passages (converged configuration). a) no transition; b) ballast-slab transition; c)culvert with approach slabs.

4 Conclusions and Contributions

In this work, non-linear connections for a lattice model capable of reproducing the compaction behaviour of ballast are presented; these connections are afterwards used to study the settlement behaviour of ballasted tracks in zones of stiffness variation. The non-linear properties of the lattice can be tuned to the results from lab tests (cyclic loading of ballast layers) and then be used for a wide variety of foundation conditions, since the tests only account for ballast. This versatility is one of the strongest points of the proposed non-linear connections. The non-linear connections are able to capture phenomena like gradual settlement accumulation, the associated stiffening of the layer, and load dependent settlement.

The non-linear connections are used to simulate the settlement accumulation due to successive train passages on tracks presenting distinct transition types: i) a zone with variations at the foundation, in which a culvert crosses under the track; ii) a transition from ballast track to slab track. In the first transition type, there are small differences in the settlement profiles over the culvert and approach slabs (when compared to the free part of the track), but these difference are insufficient to increase the wheel-rail contact forces or to lead to hanging sleepers. On the contrary, the ballast-slab transition scenario showed that as ballast compacts, the unlevelled rail leads to amplification of contact forces and to hanging sleepers. Nonetheless, the two scenarios showed that ballast compaction, on its own, is insufficient to explain the levels of deterioration of the vertical geometry of the track observed in practice. Generally, other phenomena such as differential geotechnical/autonomous settlement of the foundation must be taken into account to explain the geometrical degradation process at these locations.

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