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Modelling of the long-term behaviour of transition zones: Prediction of track settlement

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ABSTRACT

Transition zones in railway tracks are the locations with considerable changes in the vertical support structures. Typically, they are located near engineering structures, such as bridges, culverts, tunnels and level crossings. In such locations, the variation of the vertical stiffness and the differential settlement of the track (when the foundation settles unevenly) result in amplification of the dynamic forces acting on the track. This amplification contributes to the degradation process of ballast and subgrade, ultimately resulting in the deterioration of vertical track geometry (settlement).

To analyse and predict the accumulated settlement of the track in transition zones, a methodology using the iterative procedure is proposed. The methodology includes the finite element simulations of the vehicle-track and sleeper-ballast interaction during a train passing a transition zone; and iterative calculations of accumulated track settlement, based on an empirical model for ballast settlement.

The simulations are performed using a 3-D dynamic finite element model (explicit integration) of a track transition zone, which accounts for the differential stiffness and the differential settlement of the track. Also, nonlinear contact elements between sleepers and ballast are used. As a result, the model can perform the detailed analysis of the stresses in ballast and accounts for the effects of vehicle dynamics. The model was validated against field measurements. The empirical settlement model describes the two-stage settlement of ballast and the nonlinear relationship between ballast stresses and permanent settlement.

The proposed methodology is demonstrated by calculating the track settlement in the transition zone for 60,000 loading cycles (3.5 MGT). The dynamic responses such as ballast stresses are analysed to study the effect of the settlement. The parametric study of the iteration step used in the accumulated settlement procedure has been performed, based on which the optimal step is suggested.

1. Introduction

Transition zones in railway tracks are locations with considerable changes of the vertical support structures. Typically, they are located near engineering structures, such as bridges, culverts, tunnels, and level crossings. In such locations, the variation of the vertical stiffness and the differential settlement of the track (when the foundation settles unevenly) result in amplification of the dynamic forces acting on the track. This amplification contributes to the degradation process of ballast and subgrade, ultimately resulting in the deterioration of the vertical track geometry (settlement), which typically manifests itself in a ‘dip’ in the vertical geometry profile of the track. An example of a track deflection profile obtained by the measurement train in a transition zone is shown in Fig. 1. Fig. 1 shows the signature of the track deformation under the passage of Eurailscout UFM120 [1]. This deformation signature was derived from the measured acceleration signature using a double integration method. Fig. 1 identifies the embankment and bridge lengths.

The track profile in Fig. 1 shows that two significant deflections appear before and after the bridge, indicating that the track suffers from extra settlements. Such dips are often reported in the literature [2–6]. According to a survey of nine railway companies in the US, approximately half of all railway bridges were affected by dips [7]. Such a significant irregularity in the track geometry may trigger considerable wheel-rail interaction forces, which may result in extensive damage to track components, affect passenger’s comfort, and lead to even larger permanent settlements. Ultimately, it may raise the need for additional maintenance and hence increase the life cycle costs of tracks. For example, the maintenance activities on the track in transition zones are performed 4–8 times more often than that on the open tracks in the Netherlands [8,9].

The dynamic behaviour of transition zones including level crossings

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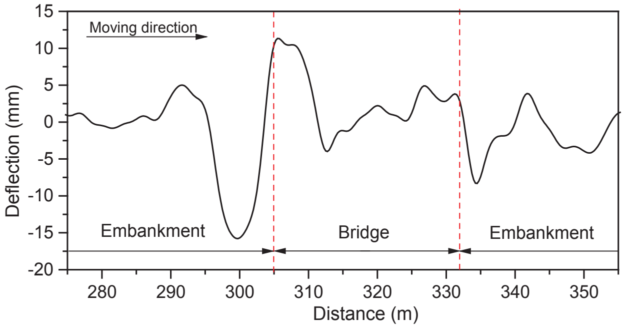

Fig. 1. Measured track deflection profile in a track transition zone in the Netherlands by EurailScout.

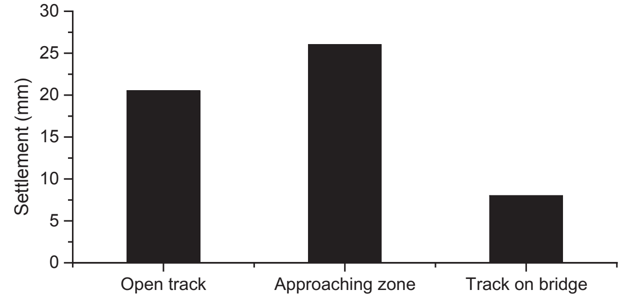

Fig. 2. Comparison of the settlement in different locations of the transition zones, plotted according to [3].

has already been studied, in [2,6,10–32]. In these studies, the short-term behaviour (i.e. behaviour due to a single passage of a train) of track in transition zones was analysed. However, in an exhaustive review of transition zones [32], Sañudo et al. indicated that the studies on the long-term behaviour of the track in transition zones are somewhat lacking. Except in [10,33], the settlement in transitions was predicted using 2D beam-spring track models combining with empirical models.

This paper presents a methodology to predict the accumulated settlement of the track in transition zones. The methodology combines a 3D FE (finite element) model of the transition zone and an empirical model for ballast settlement. The FE model has several novel features to thoroughly consider the nonlinearity of the sleeper-ballast contact (surface to surface contact [34], further explained in Section 3.1) as compared to the existing models. In addition, an iterative procedure is used to predict the settlement in transition zones, wherein the transition zone model is coupled with the ballast settlement model based on the relationship between ballast stress and settlement [35]. In addition, the parametric study of the prediction procedure is performed.

In comparison to the existing methodologies, the proposed methodology can predict more precisely the settlement of transition zones, albeit the process would be computationally more expensive. The highlights of the methodology are as following:

- Behaviour of hanging sleepers in transition zones is more accurately described, since contact elements are used to model the interface between sleepers and ballast.
- More realistic settlement curve of rails and the hanging distance of sleepers can be obtained, using pre-loading step in the explicit FE analysis.
- The stresses in ballast and the effects of vehicle dynamics can be calculated.
- The nonlinear relationship between ballast stresses and settlement is considered in the settlement model.

The methodology provides a basis to study the growth of ballast settlement and the geometry degradation of tracks in transition zones. Also, the dynamic responses due to the ballast degradation can be analysed. The methodology can also be used for the comparative analysis of various transition designs. The methodology was originally presented in [36]. The main parts of the procedure are:

(I) simulation of the vehicle-track and sleeper-ballast interaction during a train passing the transition zone, using the 3-D FE transition zone model, to obtain the stresses in the ballast;
(II) calculation of the track settlement for a given number of loading cycles based on the ballast stresses, using the empirical settlement model;
(III) adjusting the FE transition zone model based on the calculated settlement under each sleeper for the step (I) in the next iteration.

The paper is organised as follows. The studies on track settlement are reviewed in Section 2. The FE transition zone model, the empirical settlement model of ballast track, and the integration of models are described in Section 3. In Section 4, the iteration scheme is demonstrated by calculating the track settlement in the transition zone for 60,000 loading cycles, or 3.5 MGT (Million Gross Tonnes). Also, the dynamic responses such as the ballast stress at 0 and 60,000 cycles (3.5 MGT) are compared to study the effect of settlement. In addition, the parametric study of the iteration step is performed. Finally, conclusions are drawn in Section 5.

2. Theory of settlement in transition zones

In [3], the average track settlements on open tracks, approaching zones and bridges were measured on several transition zones, as shown in Fig. 2. The settlement is accumulated within one maintenance interval, which was 80 MGT of traffic. This figure shows that the settlement on the open track is higher than that on the bridge, and the settlement on the approaching zone is higher than that on the open track. It should be noted that the tracks on bridges in this study are ballast track; therefore the settlement of tracks on bridges is not zero. These findings in Fig. 2 are in agreement with the deflection of the track shown in Fig. 1.

The high settlement appearing in transition zones usually results from the following three aspects:

(I) the differential settlement between ballast tracks and engineering structures, which can also be considered as the geometrical irregularity, playing a major role in the degradation process of transition zones [4,18,19,37–39];
(II) the significant abrupt change in the vertical stiffness of tracks;
(III) geotechnical, construction and maintenance issues [3,7].

Note that both factor (I) and (II) lead to the increase of wheel loads, which in turn increases track settlement [2,10]. The higher settlement of ballast tracks as compared to that of engineering structures is mainly due to the breakage and pulverisation of ballast, compaction of ballast and soil layer, and soil-water response [40]. After construction or tamping of open tracks, the permanent settlement of ballast can be divided into two stages, according to the deformation mechanism of ballast [41–44], as schematically shown (the solid line) in Fig. 3. Stage 1 is the rapid compaction and abrasion process that happens within 3–6 months [41,42]. In this stage, the main deformation mechanism is the volumetric compaction of particles. Stage 2 is the normal settlement process happening until the end of a maintenance interval, wherein the main deformation mechanism is the frictional sliding of particles [41,45–48]. The settlement growth for open tracks is nonlinear in stage 1, while that is almost linear in Stage 2 [41,43].

Since the tracks on engineering structures are settled much less as compared to (open) ballast tracks, differential settlement can be generated. According to the numerical simulations presented in [37,39],